INSTITUT LUMIÈRE MATIÈRE

Dépôt de nano-aimants préformés : des propriétés intrinsèques à l'auto-organisation

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Lyon 1

Outline

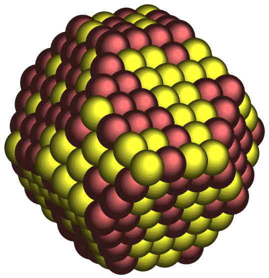
- Motivations
- Cluster deposition: originality of the LECBD technique
- CoPt nanoparticles: chemical order and magnetic anisotropy?
  - ✓ Magnetic measurements
  - ✓ Structural characterization
- Self-organization of Pt based nanoparticles on C substrates
  - ✓ Clusters deposited on graphite and carbon nanotubes
  - ✓ Pt cluster organized on graphene/Ir(111)
- Perspectives

Potential applications of magnetic nanoparticles

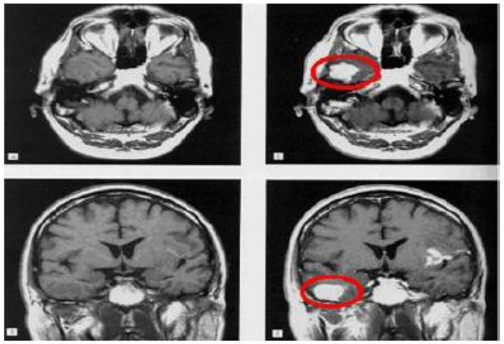
Small nanoparticles (D < 5 nm)

Size reduction effect (major importance of the surface)

→ The properties can differ from the bulk ones



2.7 nm diameter cluster (586 atoms):
45% of the atoms on the surface



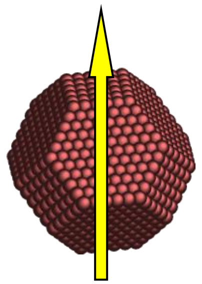
- Biological/medical applications
  - ✓ Targeted drug delivery
  - ✓ Hyperthermia (cancer treatment)
  - ✓ MRI contrast agent
- Catalysis
- Spintronic devices
- Magnetic storage applications

→ High density storage (> 1 Tb/inch^2)

Clusters as "nano-magnets"

Ferromagnetic nanoparticle as an ultimate bit of information

Monodomain particle = macrospin



Problem: **superparamagnetism**

→ Magnetization fluctuation in nanostructures

Energy barrier to switch the magnetization

→ Magnetic anisotropy energy: $E_{ani} = K_{eff} V$ (K_{eff} is the anisotropy constant)

It controls the stability (temporal, thermal, magnetic) of nanomagnets

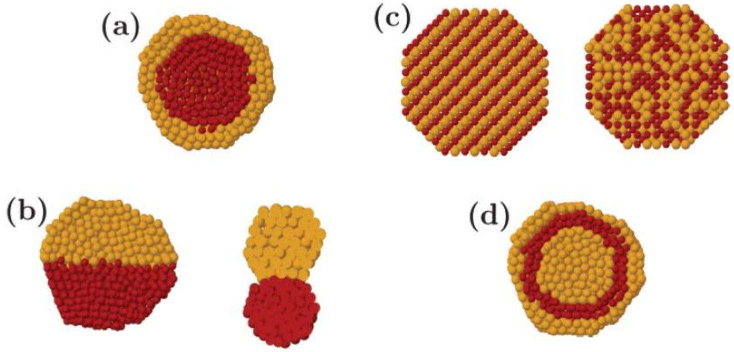
Magnetization switching frequency: $\nu = \nu_0 \exp(-E_{ani} / k_B T)$

Ex.: for a 3 nm diameter Co particle, the magnetic moment switches each 2 ns

Stable nanomagnets (magnetic storage) → Increase K_{eff}

- ✓ Surface/interface effect
- ✓ Volume effect (cluster structure, composition) → Alloys

Bimetallic nanoparticles

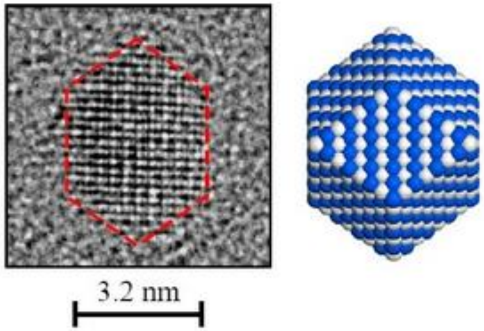


- Two types of atoms:
  additional degree of freedom
- Nanoalloys, bimetallic particles:
  different types of structures

New properties, combination of properties, at the nanoscale

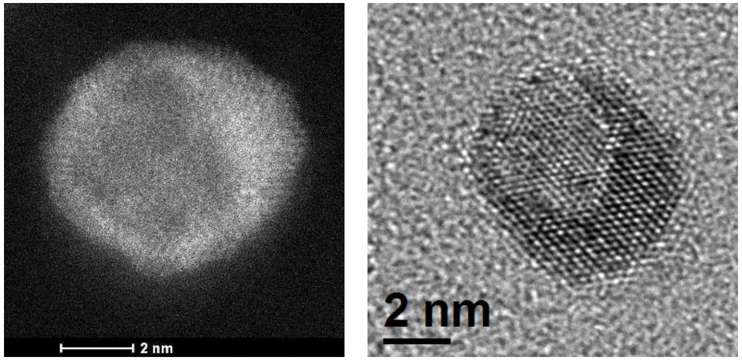
Ex. FeRh

A. Hillion *et al*., Phys. Rev. Lett. **110**, 087207 (2013)



Ferromagnetic order stable at low T
(instead of anti-ferromagnetic)

Ex. CoAu



Original structures, magneto-plasmonic interest

Our general research axis: link between the structure (including the particles environment) and the magnetic properties.

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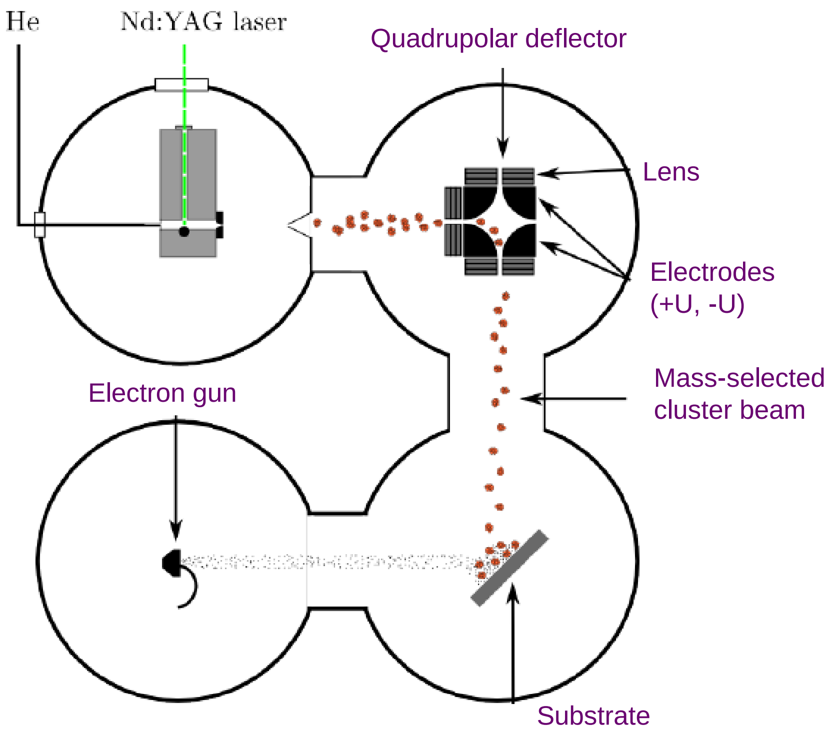
Deposition of preformed clusters (physical route)



A. Perez *et al.*, Int. J. Nanotechnol. **7**, 523 (2010)

R. Alayan *et al.*, Rev. Sci. Instrum. **75**, 2461 (2004)

Low energy cluster beam deposition, based on a laser vaporization source

✓ Deposition under ultra-high vacuum

✓ Adjustable composition (target)

✓ Capping or co-deposition in a matrix

➡ • Protect the particles
• Avoid coalescence

✓ Possibility of size selection (quadrupolar electrostatic deflector)

All the particles have the same velocity

➡ Selection of kinetic energy = mass selection

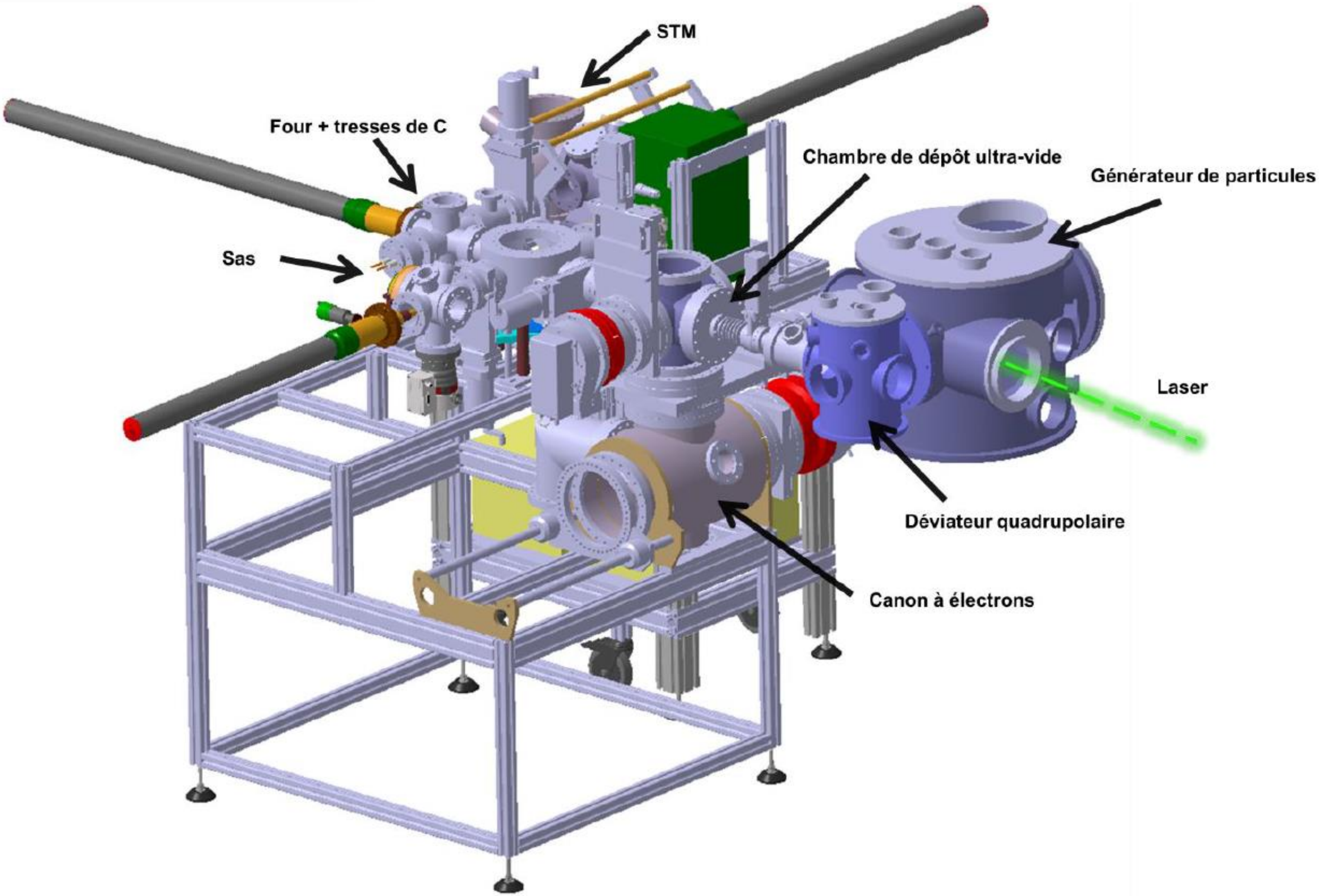


Figure I-4 : Représentation 3D de la source triée en taille.

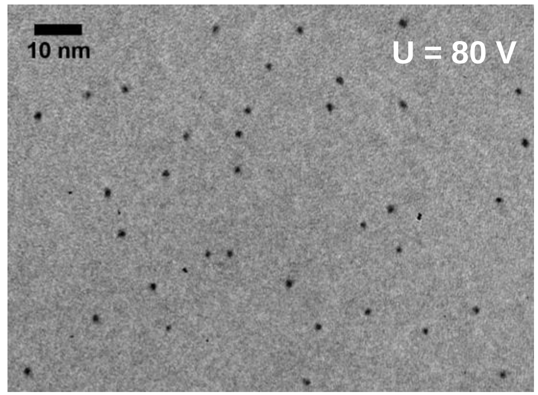
Nanoparticle assemblies

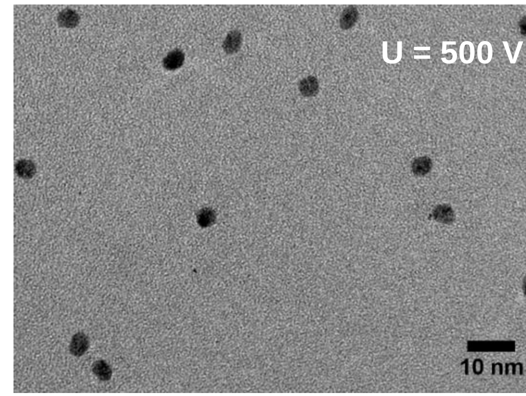
Typical nanoparticle diameter ~ 3 nm

- Adjustable particle size, independently from the surface density.

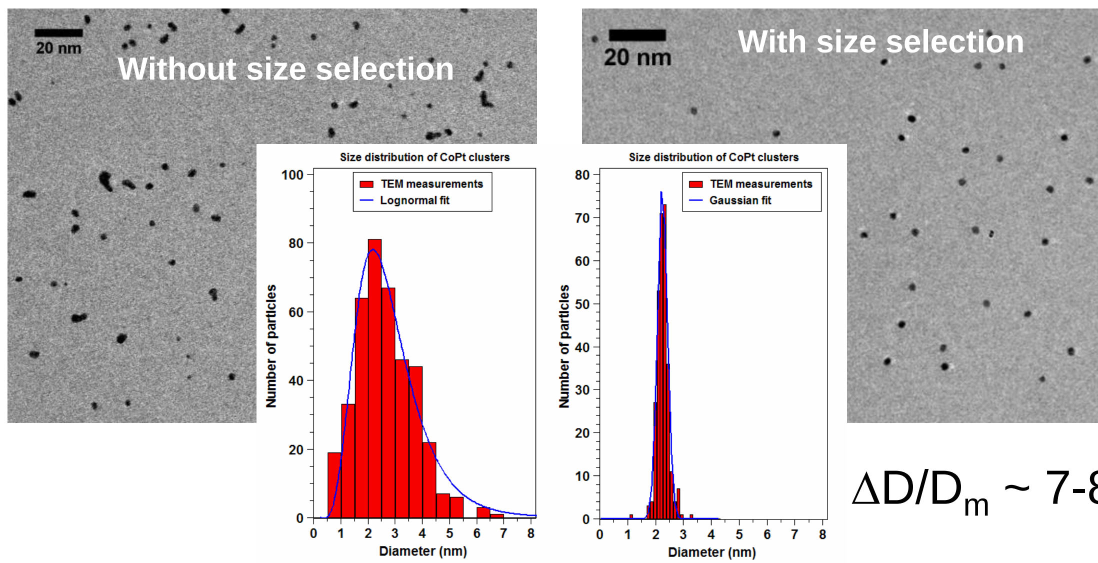
⇓

Diluted assemblies (avoid interactions)





CoPt nanoparticles



- Relative diameter dispersion lower than 10 % with size selection.

$\Delta D/D_m \sim 7\text{-}8\ \%$

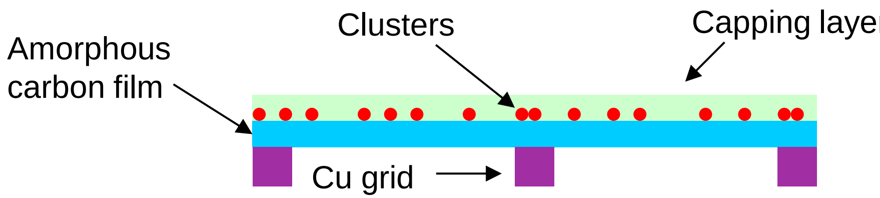
- Random deposition.

Nanoparticle samples

- ✓ **2D cluster films**

➡ With or without a capping layer

For example, for TEM studies, with an amorphous carbon capping.

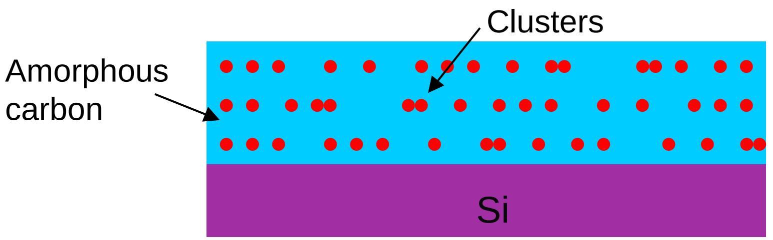


- ✓ **Multilayers (“Mille-feuille”)**

Diluted 2D cluster layer:

➡ { Equivalent thickness ~0.5 Å
Mean interparticle distance ~10 nm

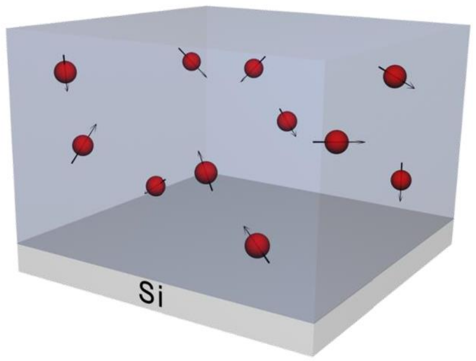
Matrix as a spacer.



For example, for magnetic measurements.

- ✓ **Diluted 3D assemblies**

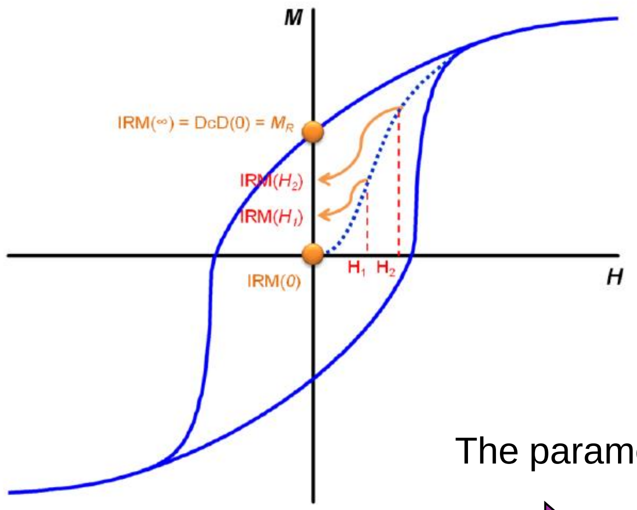
Clusters embedded in a co-deposited matrix.



This approach allows ex-situ characterization by many techniques (EXAFS, XRD, XMCD, TEM, SQUID…)

Diluted samples to avoid interactions

Very sensitive method to detect magnetic interactions



Isothermal remanence magnetization (IRM):

Starting from a demagnetized state, measurement at remanence after application of a magnetic field H.

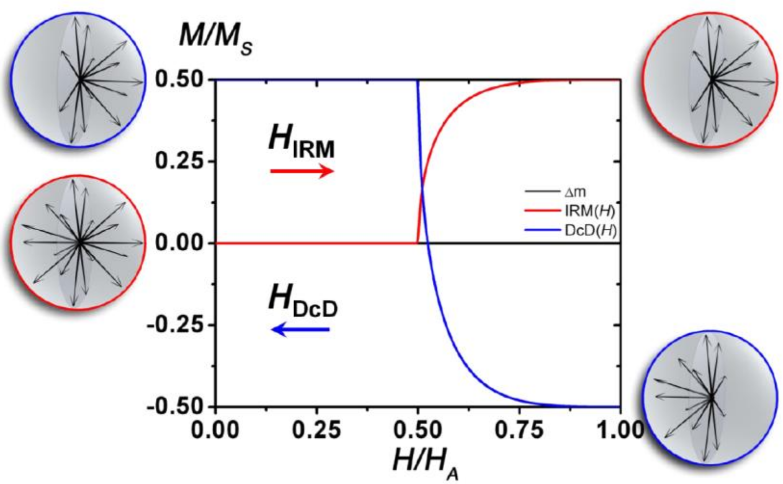
➡ Irreversible switching of some macrospins.

Dc demagnetization (DcD):

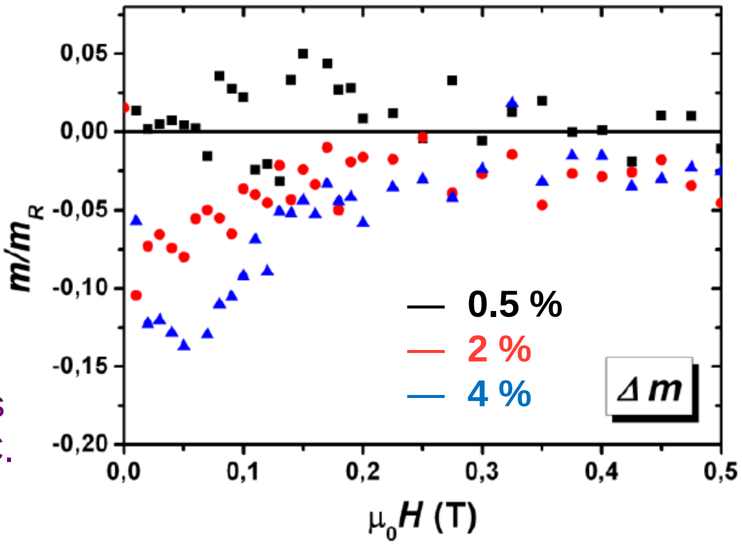
Same as IRM, but starting from m_R (after saturation).

The parameter $\Delta m = DcD(H) - \left(m_R - 2\,IRM(H)\right)$ is equal to zero with no interaction.

➡ **With a volume concentration < 1 %, interactions are negligible.**



Co clusters diluted in C.



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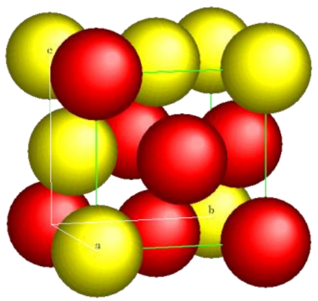
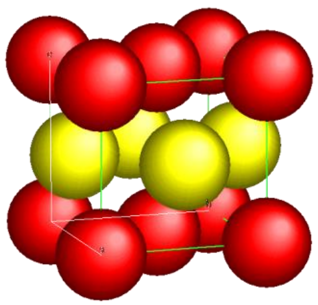
CoPt alloy: bulk



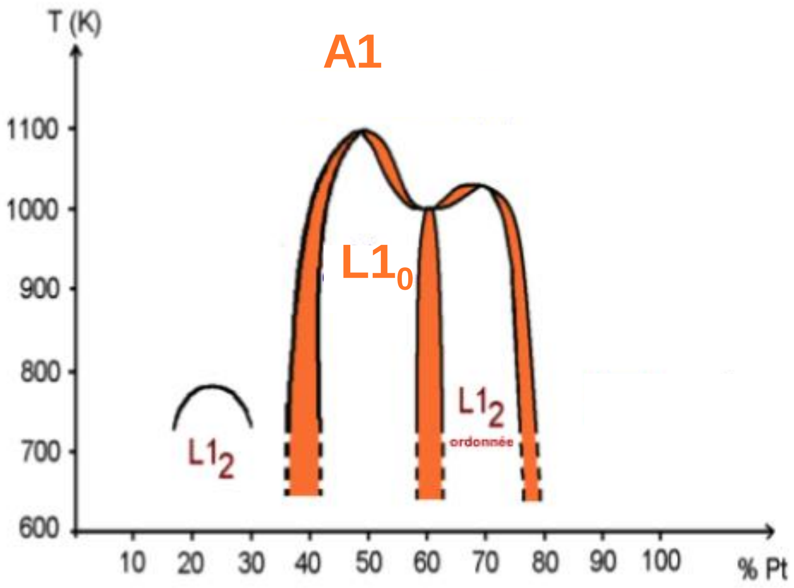
A1 phase

- Chemically disordered
- fcc cell



$L1_0$ phase

- Chemically ordered
- tetragonal cell (c/a < 1)



Phase diagram for the bulk

The $L1_0$ phase has an extremely high magnetic anisotropy constant (K_{eff}~ 5 MJ/m^3)

→ Magnetocrystalline anisotropy (due to the Co/Pt stacking)

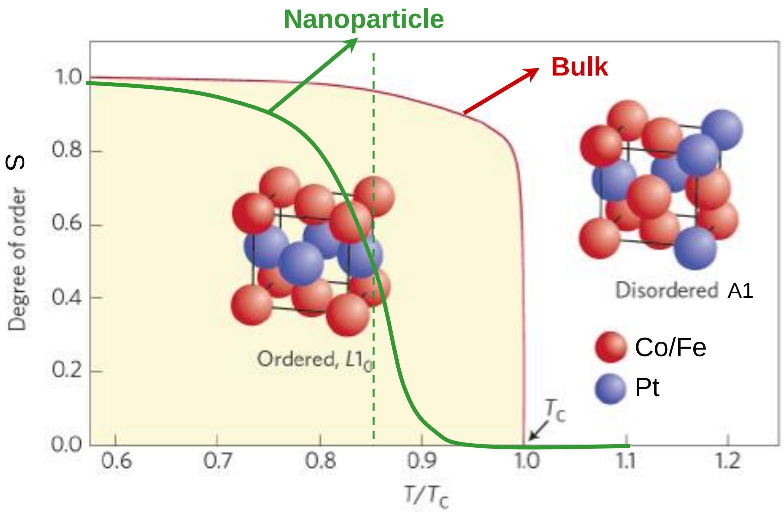
Common feature to 3d-5d magnetic alloys (FePt etc.)

The $L1_0$ phase is the stable one at room temperature, but A1 is metastable

CoPt alloy nanoparticles

- Chemical ordering by annealing

→ Synthesis itself is a challenge (well defined size, no coalescence, no pollution…)

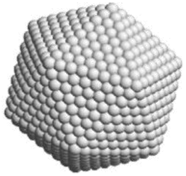


- Chemical order phase transition shifted and smoothed for nano-sizes

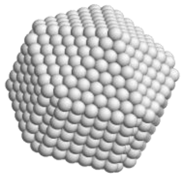
→ Threshold size for the stability of the $L1_0$ phase?

D. Alloyeau *et al*., Nature. Mater. **8**, 940 (2009) ;
K. Sato, Nature Mater. **8**, 924 (2009).

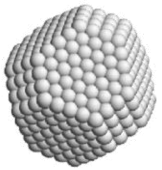
- As a function of size, competition between different geometries



Icosahedron



Decahedron

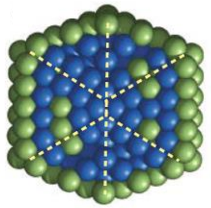


Truncated octahedron

Size reduction effects

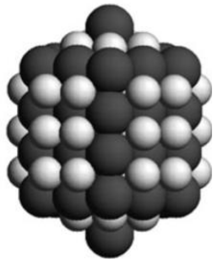
- Several theoretical predictions

→ A decahedron with a “$L1_0$” order should be favorable

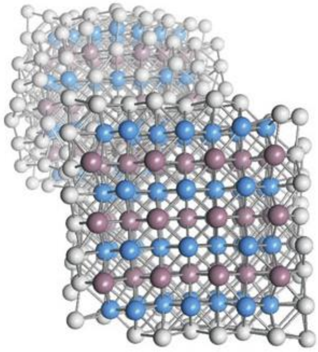


Core–shell icosahedron with depleted subsurface shell

M. Grüner *et al.*, *Phys. Rev. Lett.* **100**, 087203 (2008)



G. Rossi *et al.* *Faraday Discuss.* **138**, 193 (2008)



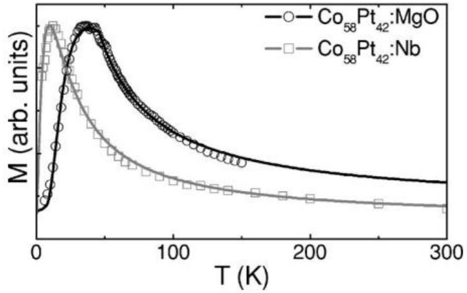
$Fe_{80}Pt_{67}Al_{162}$

C. Antoniak *et al.*, Nat. Commun. **2**, 528 (2011).

- Influence of the environment (interface, magnetically dead layer, inter-particle interactions…)

↓

Intrinsic properties of the nanoparticles?



S. Rohart *et al.*, Phys. Rev. B **74**, 104408 (2006).

The intrinsic magnetic properties of nano-sized chemically ordered CoPt particles are very difficult to determine reliably.

→ Combine **structural** and **magnetic** characterizations of CoPt nanoparticles.

✓ Magnetic measurements on CoPt particles

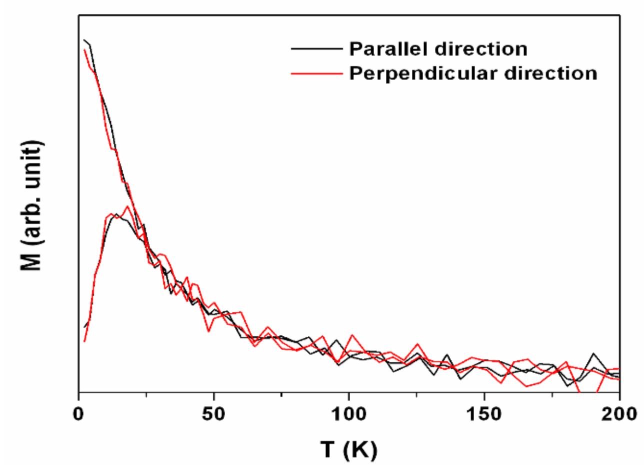
- CoPt nanoparticles embedded in an amorphous carbon matrix

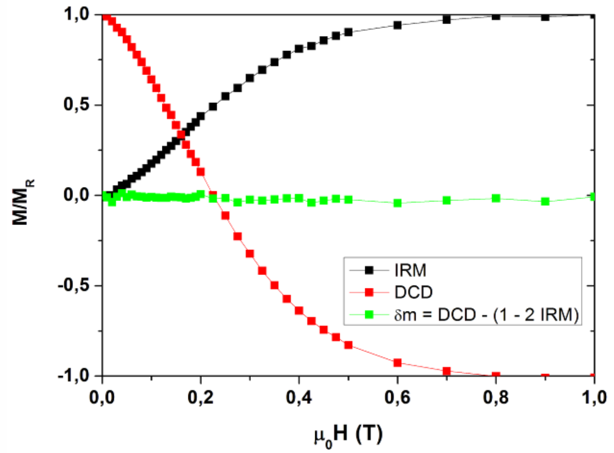
- With or without size-selection

- Before and after annealing (2h at 750 K)

  ➡ Promote chemical ordering

Verification of the absence of interactions





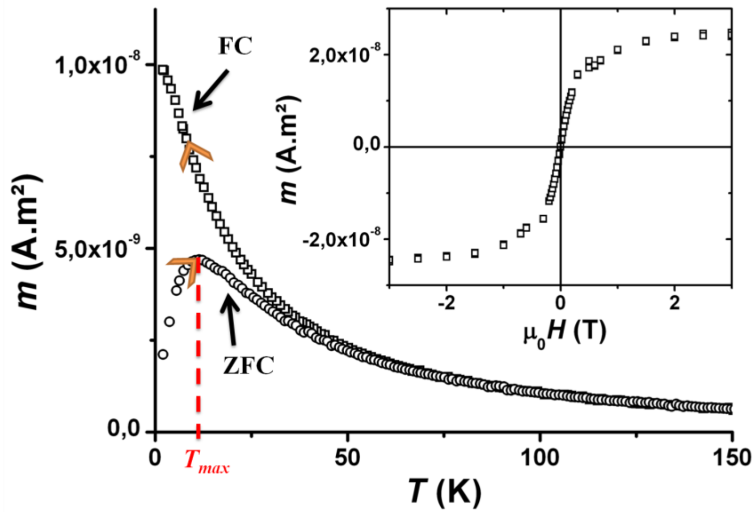
CoPt nanoparticles diluted in a carbon matrix

Magnetic anisotropy determination

Low field susceptibility measurements:

- ✓ Separation of the zero-field cooled (ZFC) and field-cooled (FC) curve
- ✓ ZFC peak at T_{max}

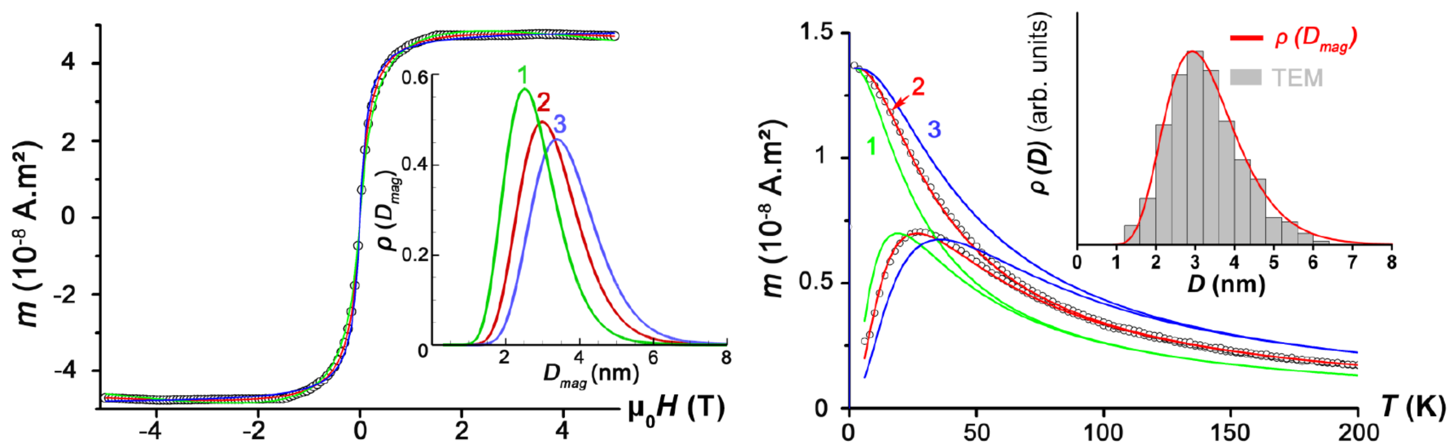
The particles, initially blocked, become superparamagnetic ➡ Magnetic anisotropy



"Triple fit" = Superparmagnetic loop (300 K) + ZFC/FC curves

Simultaneous fit: the curves share common parameters (size distribution etc.)

Co particles diluted in Au.



Accurate determination of the magnetic anisotropy

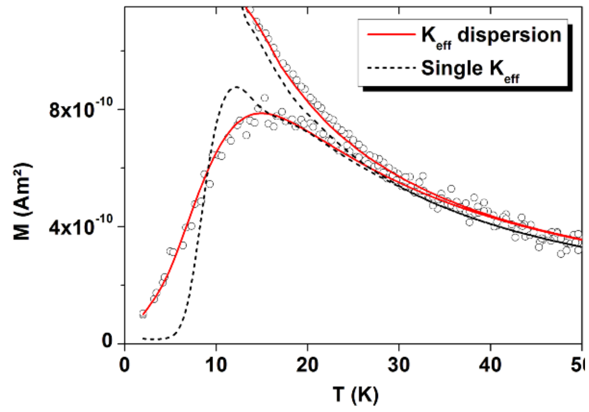
Anisotropy constant dispersion

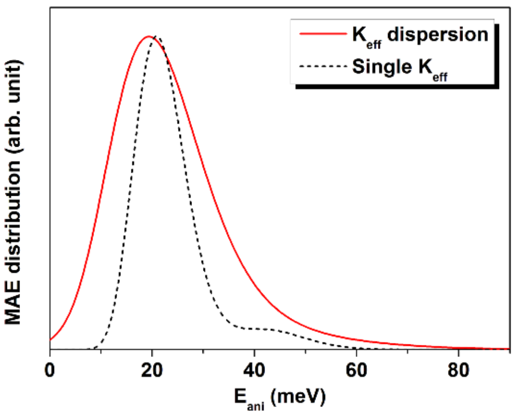
Size selected CoPt nanoparticles (3 nm), as prepared

The usual $E_{ani} = K_{eff}V$ model is no more valid ➡ Anisotropy constant dispersion

Gaussian distribution of K_{eff} :

- ✓ Relative dispersion ~ 40%
- ✓ $<K_{eff}>$ ~ 200 kJ/m^3



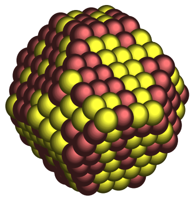


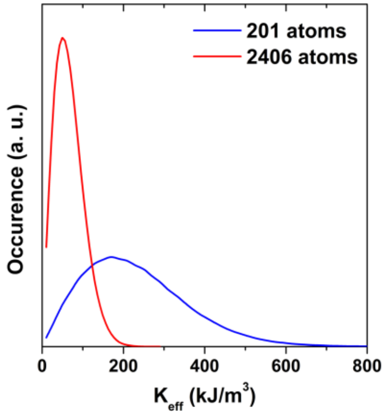
Such a K_{eff} dispersion was not detectable for particles without size selection

➡ A narrow size distribution is necessary

Physical origin?

Nanoalloy effect
- ✓ Composition
- ✓ Chemical order
- ✓ **Atomic configuration** (chemical arrangement)



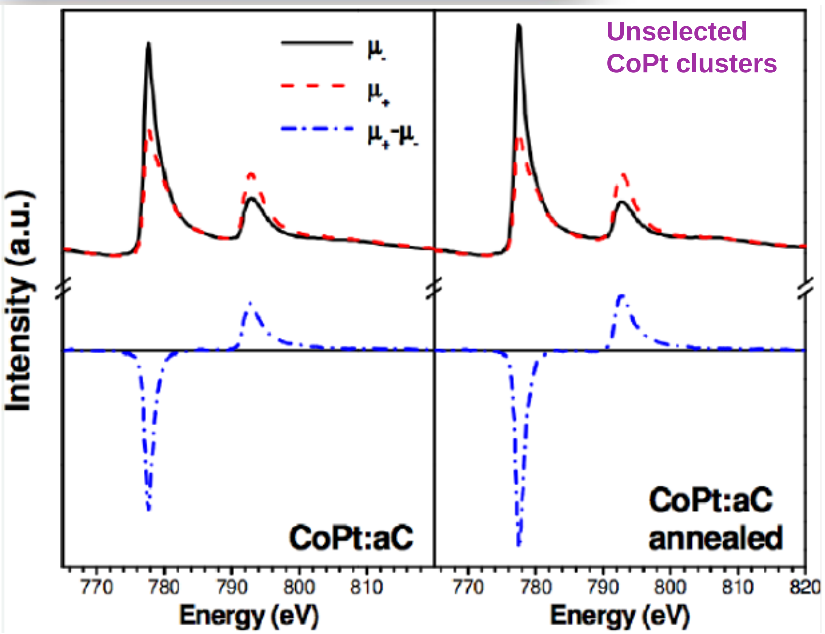


K_{eff} distribution calculated for chemically disordered CoPt particles

F. Tournus *et al*., Phys. Rev. B **81**, 220405(R) (2010)

F. Tournus *et al*., IEEE Trans. Magn. **44**, 3201 (2008)

X-ray magnetic circular dichroism (XMCD)



Absorption at the Co $L_{2,3}$ edge

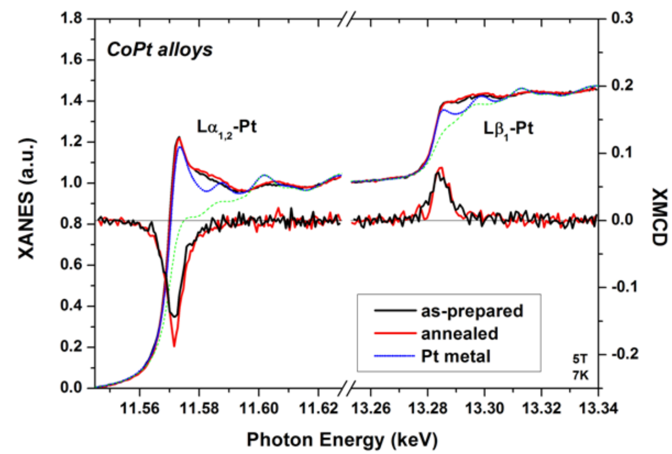
➡ Co magnetic moments

	m_S	m_L	m_L/m_S
As prepared	1.70 μ_B/at	0.12 μ_B/at	0.071
Annealed	1.91 μ_B/at	0.18 μ_B/at	0.094

✓ No Co oxidation, no “dead layer”

✓ Very high m_S value (Co bulk = 1.6 μ_B/at)

✓ Increase of m_S, m_L and m_L/m_S upon annealing



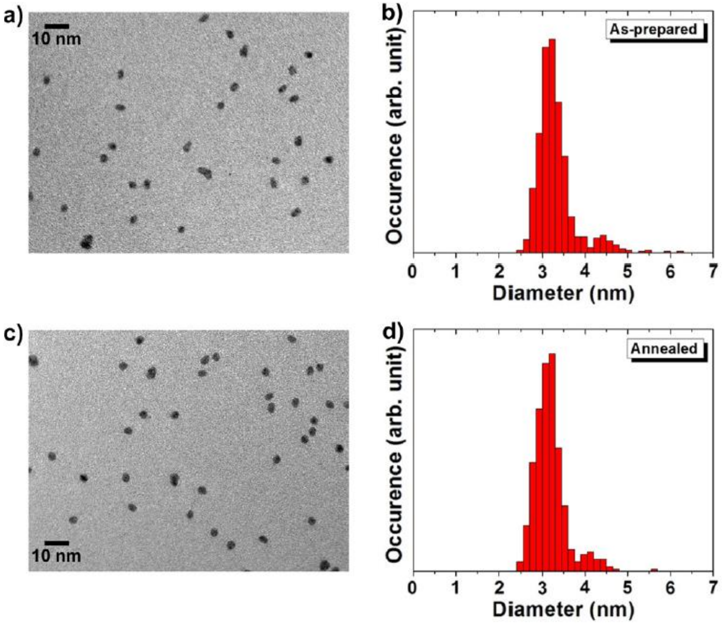
Annealing induces a change of the magnetic moments

➡ A1 → $L1_0$ chemical ordering?

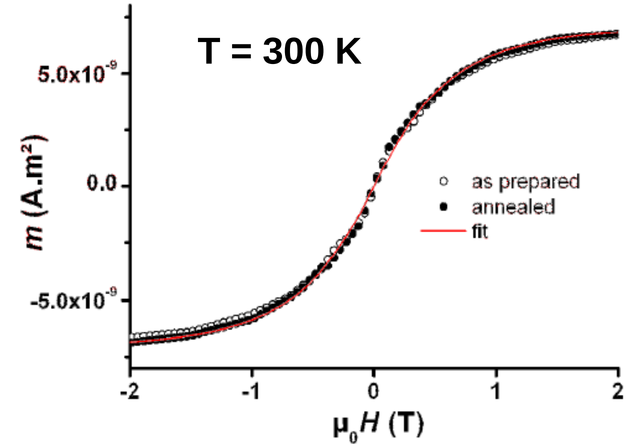
The Pt magnetic moment also increases (from 0.47 to 0.52 μ_B/at)

F. Tournus *et al.*, Phys. Rev. B 77, 144411 (2008).

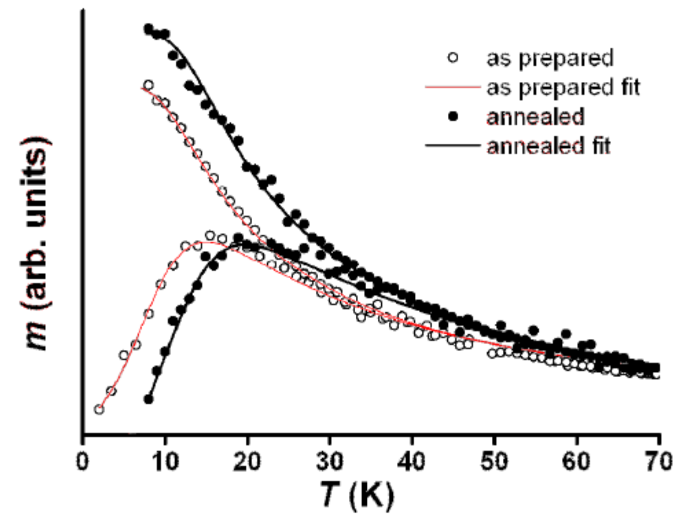
Magnetic anisotropy evolution upon annealing



No modification of the particle size upon annealing



V. Dupuis *et al.*, IEEE Trans. Magn. **47**, 3358 (2011).



Evolution of the magnetic anisotropy

	As prepared	Annealed
D_m (nm)	3.12 ± 0.1	3.12± 0.1
ω (nm)	0.22 ± 0.05	0.22± 0.05
K_{eff} (kJ.m^{-3})	218 ± 20	293 ± 30
ω_K (kJ.m^{-3})	37% ± 5%	28% ± 5%

This increase is **much smaller** than what is observed in the bulk

To fix the ideas: with K_{eff} = 5 MJ/m^3 and D = 3 nm ➡ T_B = 200 K

Magnetic properties from a global fit

To go further: global fit, including a low T hysteresis loop.

→ Significant biaxial contribution to the anisotropy.

	As prepared	Annealed (750 K)
D_m (nm)	3.12 ± 0.1	3.12 ± 0.1
σ (nm)	0.22 ± 0.05	0.22 ± 0.05
K_{1m} (kJ m^{-3})	200 ± 25	260 ± 25
σ_{K1}/K_{1m}	$37\% \pm 5\%$	$31\% \pm 5\%$
K_2 (kJ m^{-3})	100 ± 25	150 ± 25

Size-selected CoPt nanoparticles (D = 3 nm) embedded in amorphous C

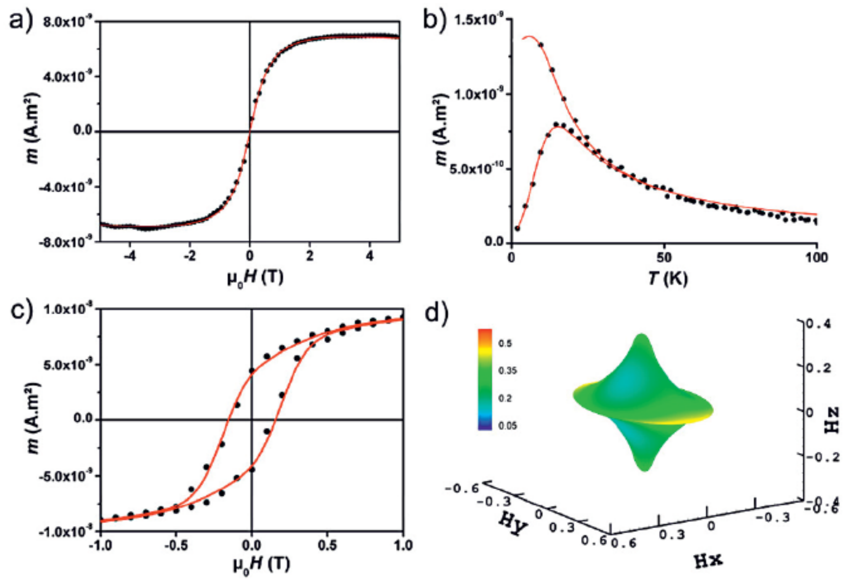


Fig. 3. (Color online) Hysteresis loops at 300 K (a), at 2 K (c) and ZFC/FC (b) for as-prepared CoPt nanoparticles embedded in C matrix. The solid lines correspond to the fit. Mean astroids associated to the biaxial fit (d).

As prepared

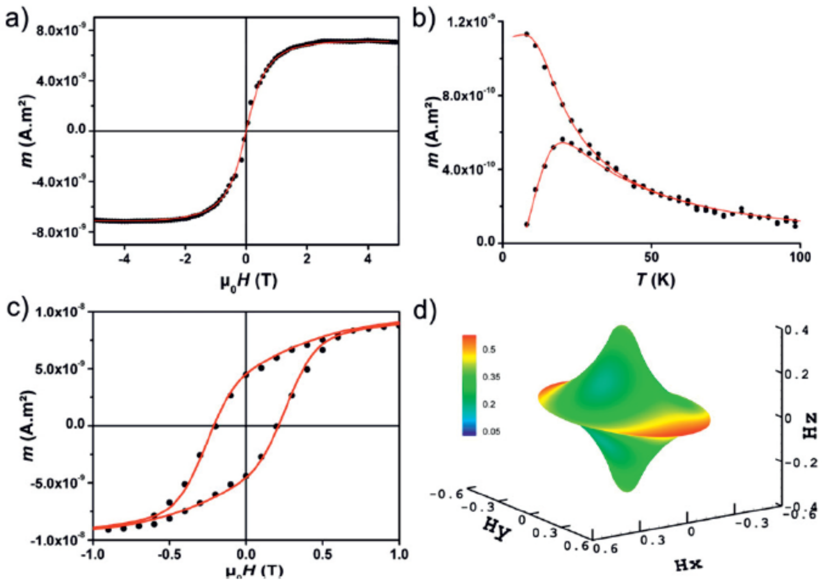


Fig. 4. (Color online) Hysteresis loops at 300 K (a), at 2 K (c) and ZFC/FC (b) for annealed CoPt nanoparticles embedded in C matrix. The solid lines correspond to the fit. Mean astroids associated to the biaxial fit (d).

Annealed

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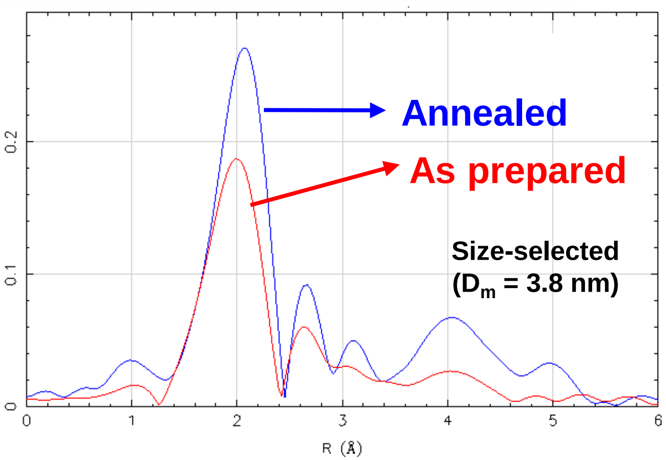
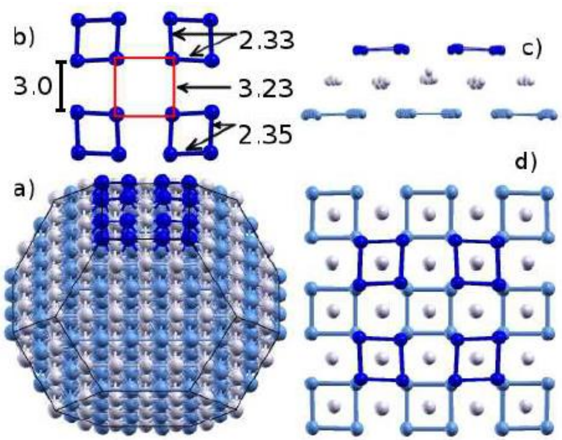
✓ Structural characterization of CoPt particles in C

- EXAFS measurements (Extended X-ray Absorption Fine Structure)
- HRTEM observations

Chemical order and relaxation



N. Blanc *et al*., Phys. Rev. B **87**, 155412 (2013)
V. Dupuis *et al*., Eur. Phys. J. B **86**, 1 (2013)



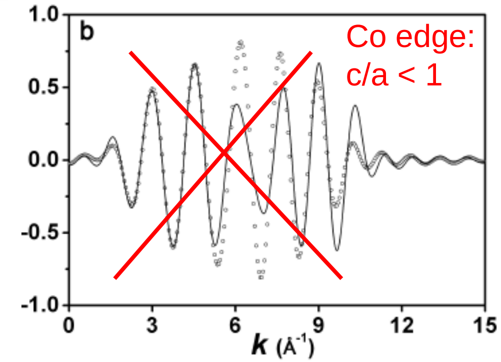
EXAFS measurements: probe the local environment of one type of atoms

- Drastic change upon annealing
- Evolution of N_{Co}/N_{Pt}

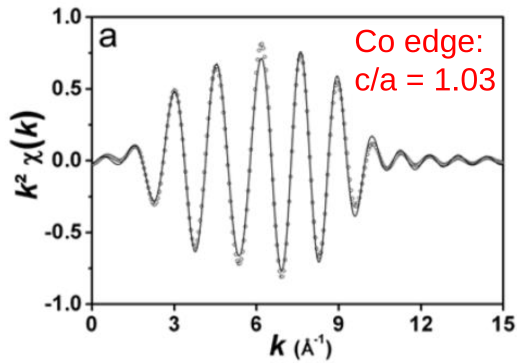
A1 → $L1_0$ transition

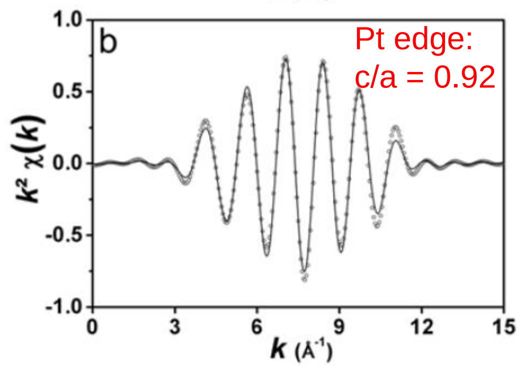
Apparent c/a ratio

Different around Co and Pt atoms:
$d_{Pt\text{-}Pt} \neq d_{Co\text{-}Co}$



Tetragonalization different from the bulk

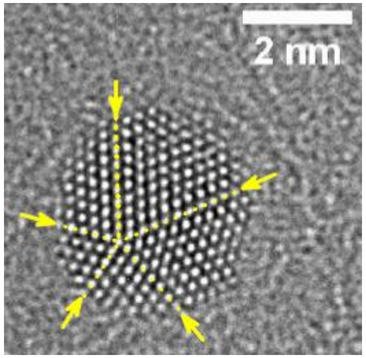




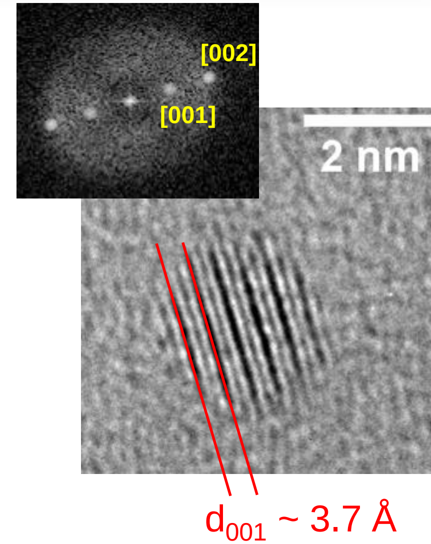
DFT calculations: “$L1_0$ like” structure

Strong relaxation of the Co-Co distances

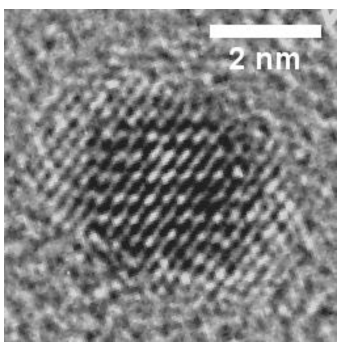
Transmission electron microscopy



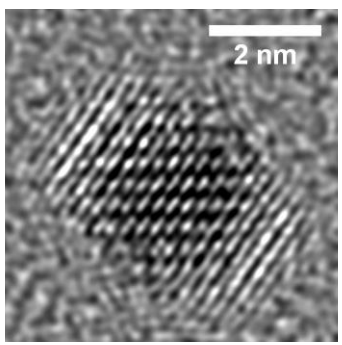
- ✓ Coexistence of fcc and multiply-twinned particles
- ✓ No chemical order before annealing
- ✓ $L1_0$ contrast ([001] peak) after annealing, even for the smallest particles



[110] orientation



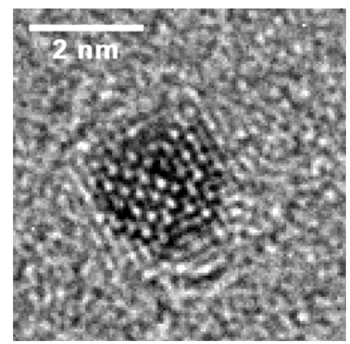
Exp.



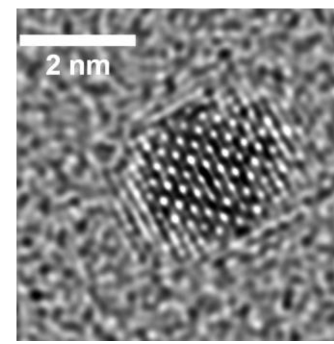
Simul.

Experiment vs. simulations

[001] orientation



Exp.



Simul.

But, chemical order is **not necessarily visible** (particle orientation, defocus)

- ✓ Challenging observations!
- ✓ Not a statistical method

Chemical order parameter of a single nanoparticle

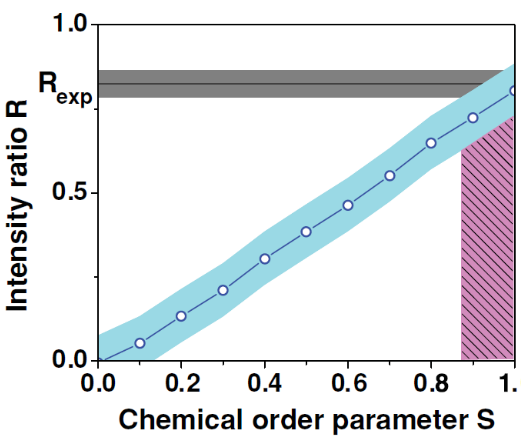
N. Blanc *et al.*, Phys. Rev. B **83**, 092403 (2011)

Method based on a simulation/experiment comparison

Determination of the imaging parameters and of the particle structure

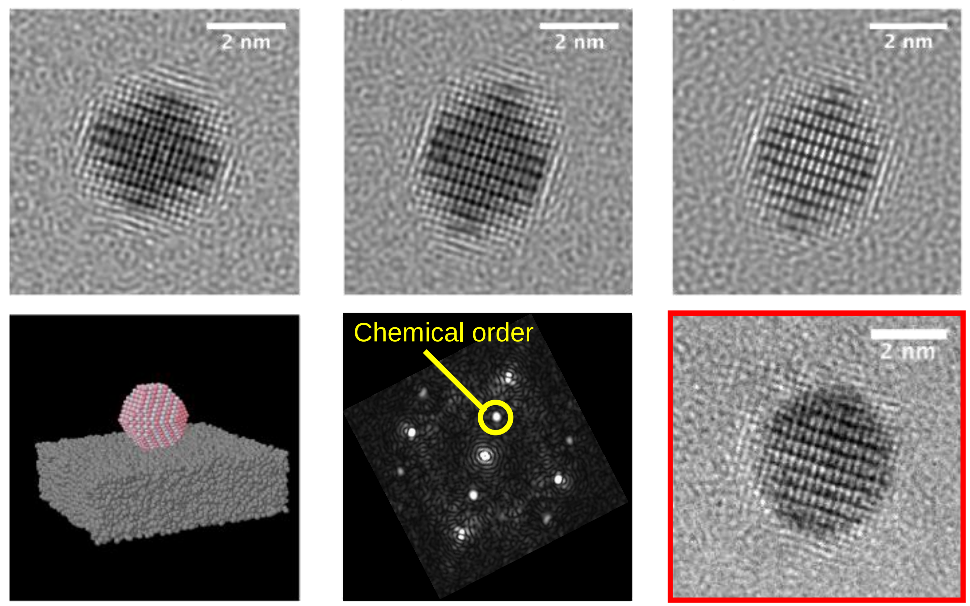
Computed ratio between a chemical order peak and a structure peak (FFT)

Theoretical curve as a function of S



Shape

Tetragonalization, orientation



Simul.

Exp. image

Model

Exp. FFT

S value for the experimental image: between 0.85 and 1

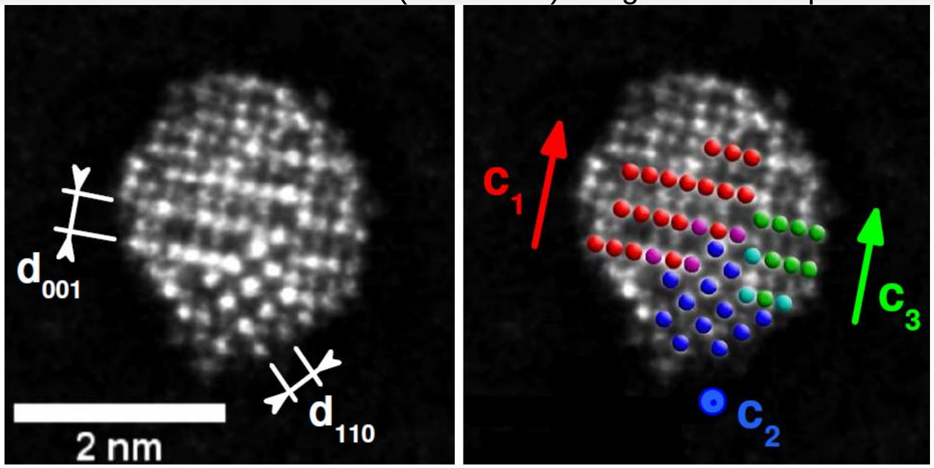
Limitations of the method: complexity, uncertainty in a general case?

Multi-$L1_0$ domain particles

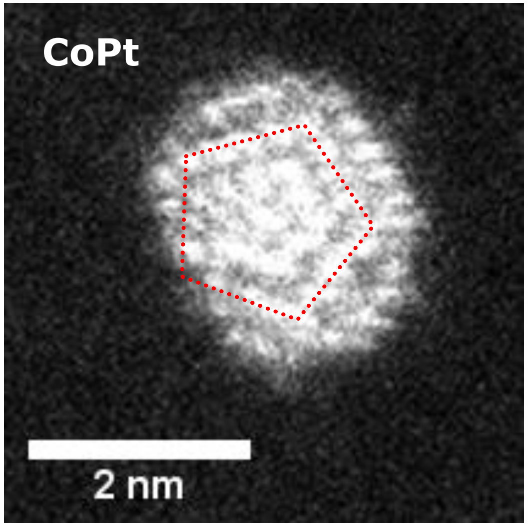
Coexistence of several $L1_0$ variants (with antiphase boundaries)

In a single-crystal particle of 2 nm diameter!

STEM HAADF (Z contrast) image of a CoPt particle



F. Tournus *et al*., Phys. Rev. Lett. **110**, 055501 (2013).

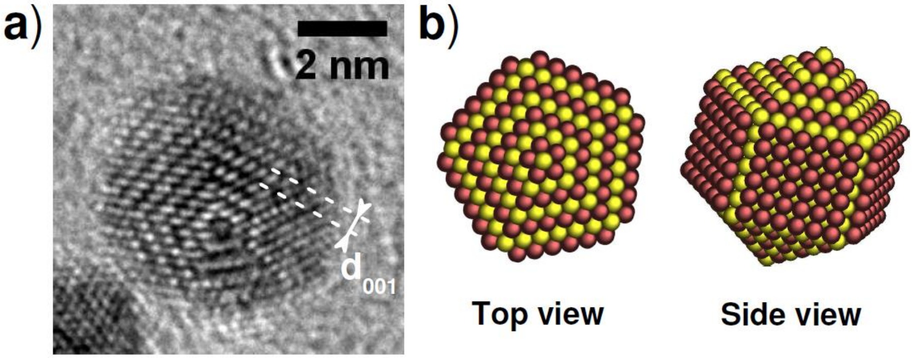


STEM-HAADF image

Decahedral particles with a chemical order

→ Five $L1_0$ domains with c axes in different directions

Theoretically predicted structure



FePt

Particles with several $L1_0$ domains → **Lowering of the anisotropy!**

Coexistence of various structures → Anisotropy constant dispersion

Conclusion on CoPt nanomagnets

✓ Effort for the determination of the intrinsic properties of CoPt nanoparticles

➡ Model systems, complementary characterizations

✓ Original properties of CoPt nanoparticles

- Magnetic anisotropy dispersion, evolution of the atomic magnetic moments
- For chemically ordered CoPt particles, the anisotropy remains much smaller than for the bulk $L1_0$ phase
- Existence of structures with several $L1_0$ domains, “exotic” geometries
- Relaxation of the inter-atomic distances because of finite size

✓ Similarities between CoPt and FePt nanoparticles

➡ But completely different magnetic behavior!

Many open questions remain…

Outline

- Motivations
- Cluster deposition: originality of the LECBD technique
- CoPt nanoparticles: chemical order and magnetic anisotropy?
  - ✓ Magnetic measurements
  - ✓ Structural characterization
- **Self-organization of Pt based nanoparticles on C substrates**
  - ✓ **Clusters deposited on graphite and carbon nanotubes**
  - ✓ **Pt cluster organized on graphene/Ir(111)**
- Perspectives

Self-organization of (bimetallic) nanoparticles

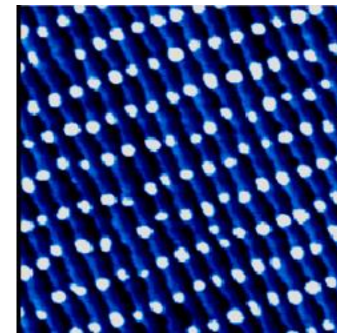
Applications: information storage…

Fundamental interest: inter-particle coupling, resonance effects…

Physical routes

- Atomic deposition on template surfaces (UHV conditions)
- Good organization for pure clusters
- Importance of the atom and particle/surface interaction

➡ Extension to bimetallic particles may be difficult



Co nanoparticles on Au(788)
V. Repain *et al.*
Euro. Phys. Lett. **58**, 730 (2002)

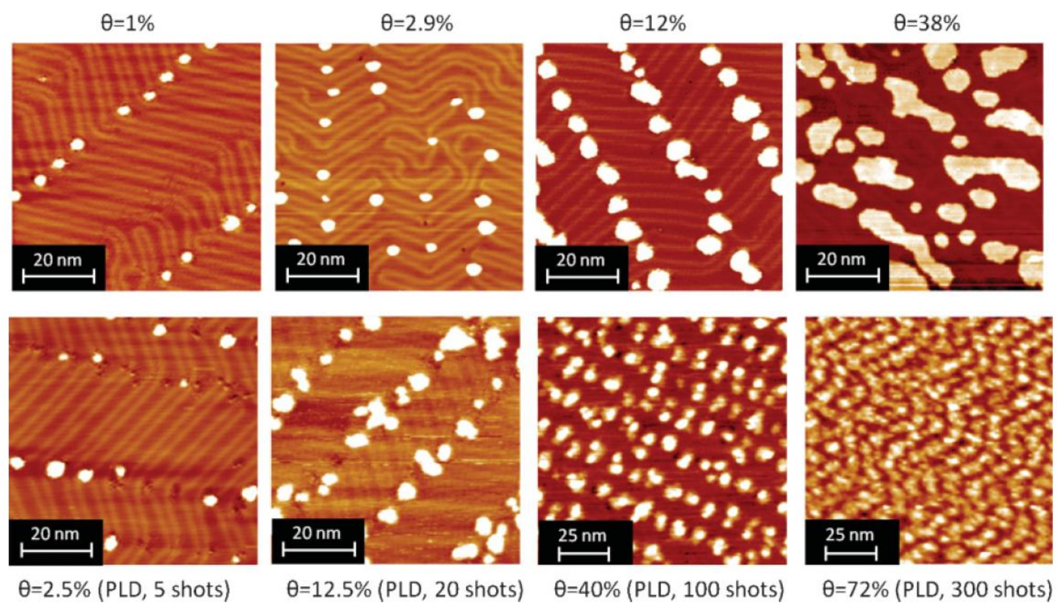
Preformed cluster deposition: an alternative approach

⬇

Not the same morphology as with atomic deposition

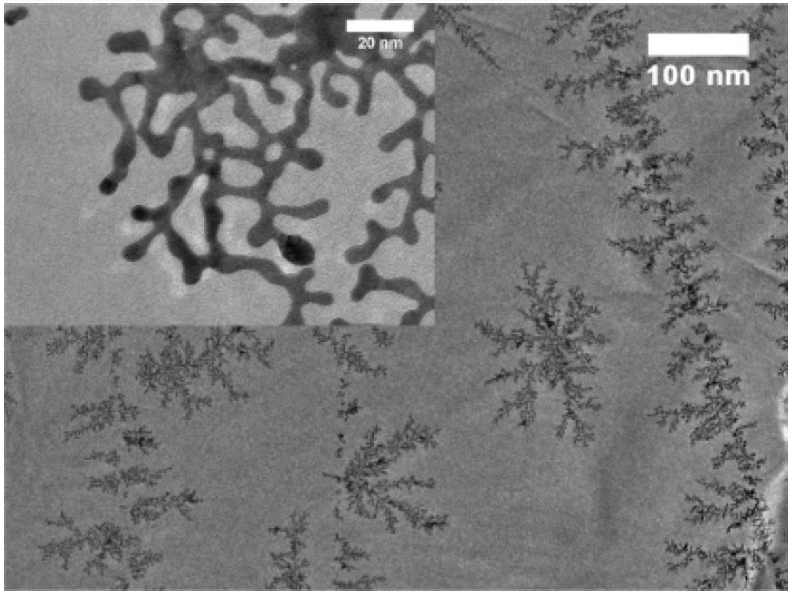
Atomic deposition

Cluster deposition



Casari et al., Phys. Rev. B **84**, 155441 (2011)

Typical case of Au



2.2 nm Au clusters deposited on HOPG

High mobility of incident clusters

Ramified islands, with partial cluster coalescence

➡ Loss of the initial particle size

Processes involved:
Diffusion, nucleation, growth, coalescence

➡ This morphology is perfectly understood

Characteristic timescales:

- τ_{dep} time between two cluster landings on the surface
- τ_{diff} time for a cluster to diffuse on a distance d
- τ_{isl} time for a cluster to be captured by an island
- τ_{coal} time needed for the coalescence of two clusters

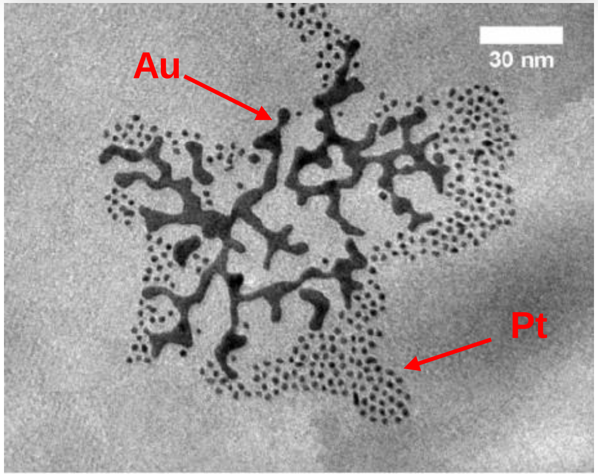
Control of the final morphology

Flux and temperature
(island density)

Temperature
(island shape)

Specificity of platinum

D. Tainoff *et al.*, J. Phys. Chem. C **112**, 6842 (2008)

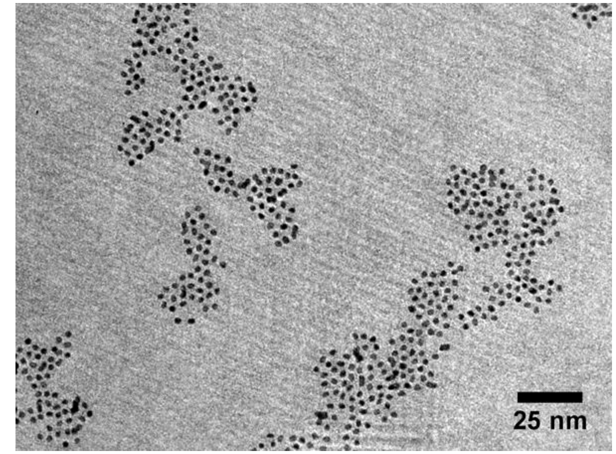


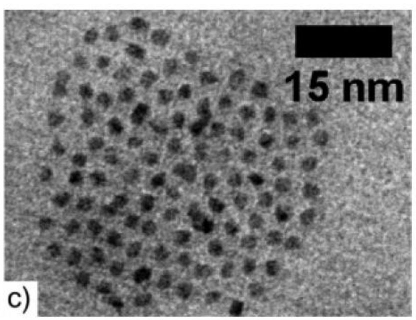
Successive deposition of Au and Pt clusters

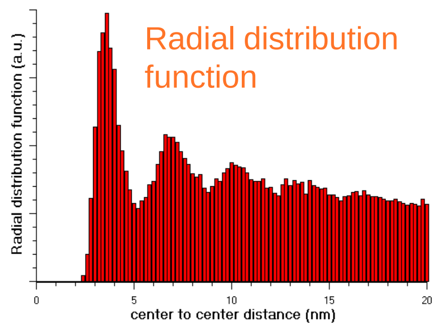
Unusual behavior of Pt clusters!

No contact, no coalescence: the cluster size is preserved

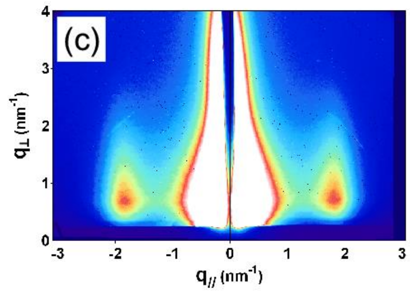
Deposition of 2.2 nm Pt clusters







Radial distribution function



GISAXS Pattern

Local hexagonal order

Edge-to-edge distance well defined (~ 1.2 nm)

This can be explained by a surface reactivity: passivation effect with residual CO.

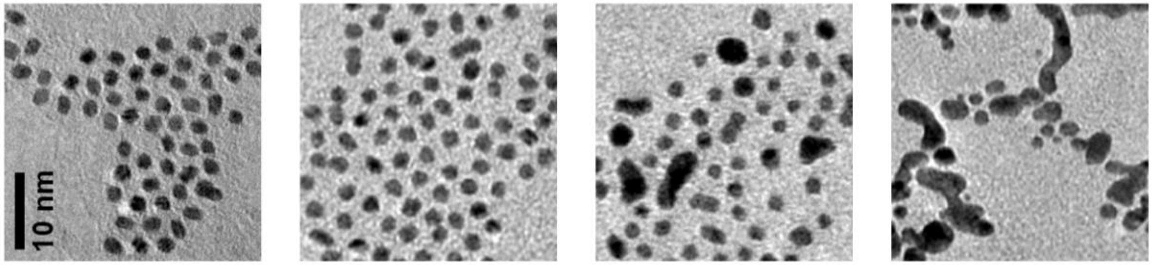
τ_{pass} time needed for cluster surface passivation

→ New parameter to control the cluster layer morphology

Specific morphology of platinum in UHV attributed to its very high reactivity

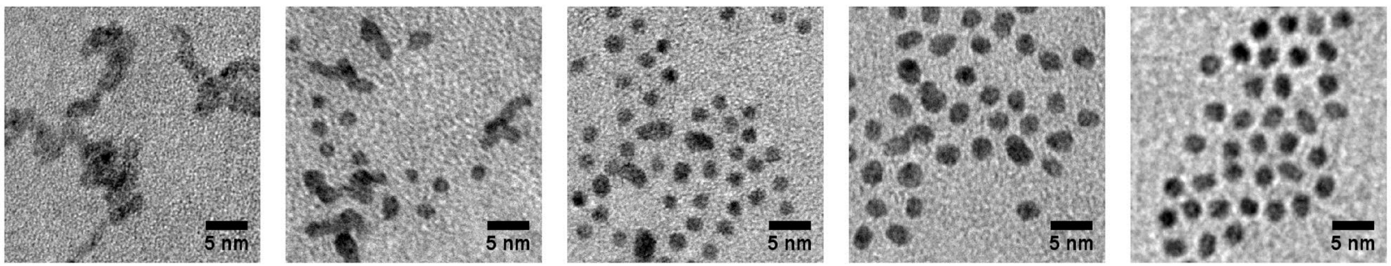
Bimetallic particles deposited on graphite

Pt | $Au_{0.2}Pt_{0.8}$ | $Au_{0.5}Pt_{0.5}$ | Au



Au_xPt_{1-x}

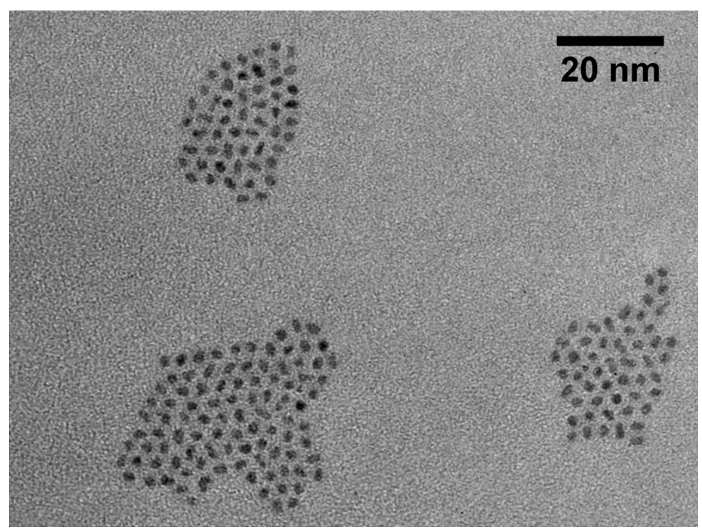
Bardotti et al., Surf. Sci. **606**, 110 (2012)



Co | Co_3Pt | CoPt | $CoPt_3$ | Pt

Co_xPt_{1-x}

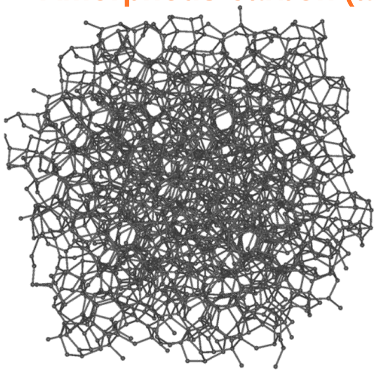
Decrease of τ_{pass} with increasing Pt content.



FePt

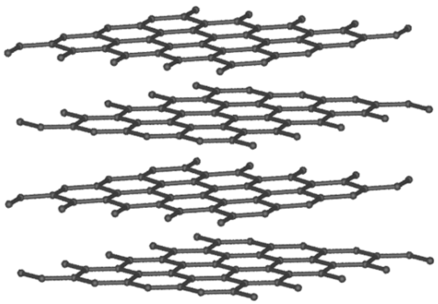
Cluster deposition on carbon nanotubes

Amorphous carbon (a-C)



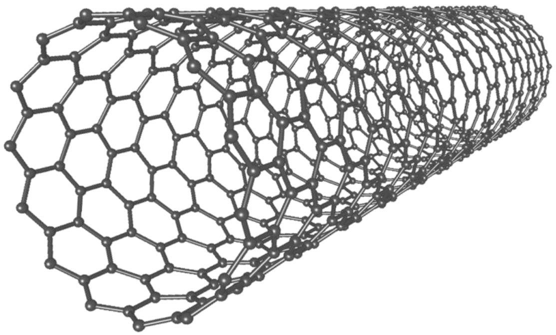
No diffusion

Graphite (HOPG)



Diffusion

Carbon nanotube (CNT)



Diffusion? Self-organization?

Technological interest

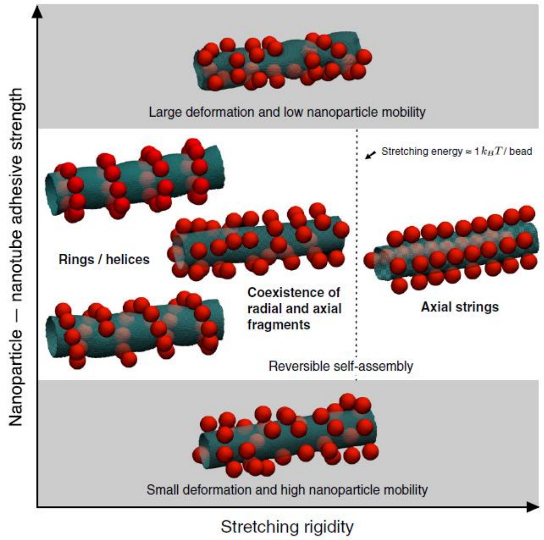
➡ Nanotube functionalization, sensors, catalysis, fuel cells…

Open fundamental questions

➡ Cluster/surface interaction

Curvature: anisotropy of the diffusion?

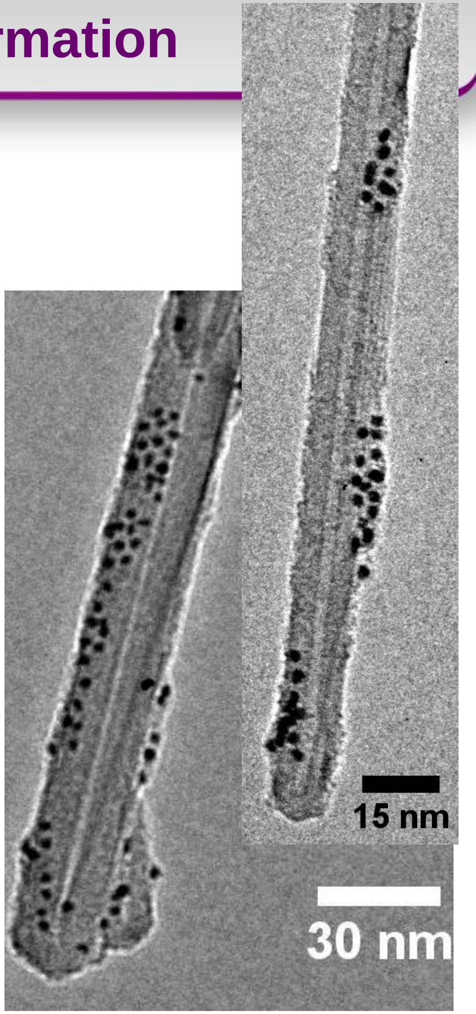
Preformed cluster deposition ➡ Model system



Pamiès et al., Phys. Rev. Lett. **106**, 045702 (2011)

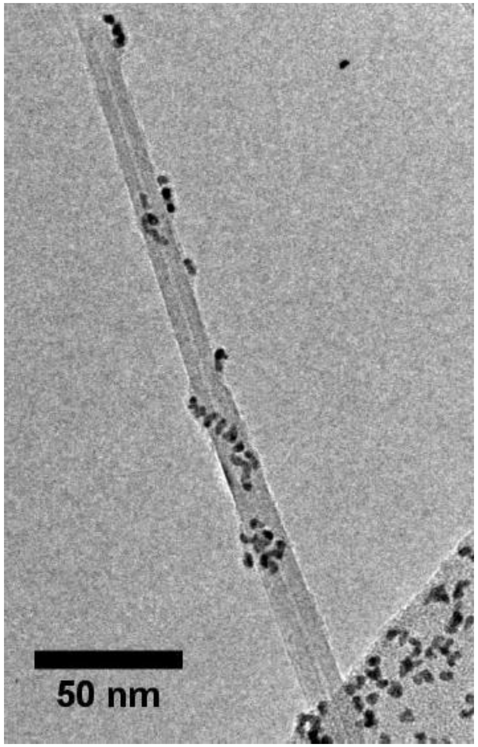
Cluster diffusion and islands formation

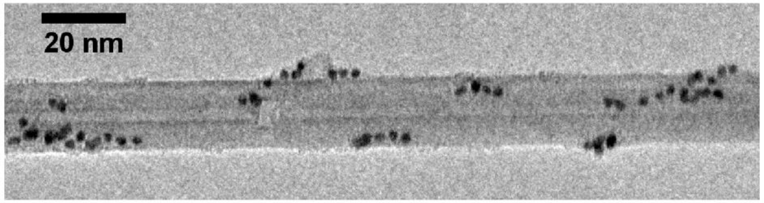
Deposition of size-selected FePt clusters on multiwall CNT (electric-arc synthesis)

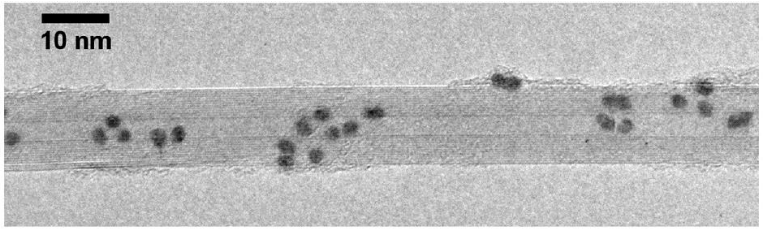


The incident clusters diffuse on the CNT surface

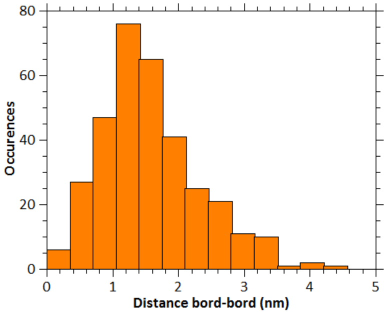
➡ Formation of “bunches” of clusters







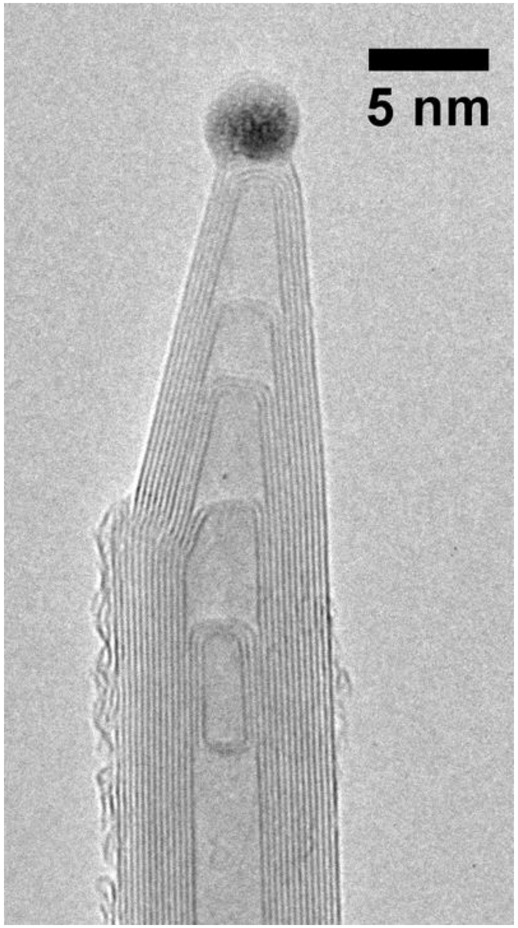
Inter-particle distance compatible with what is observed on HOPG



Nucleation on defects

L. Bardotti *et al.*, Appl. Surf. Sci. (2014), in press.

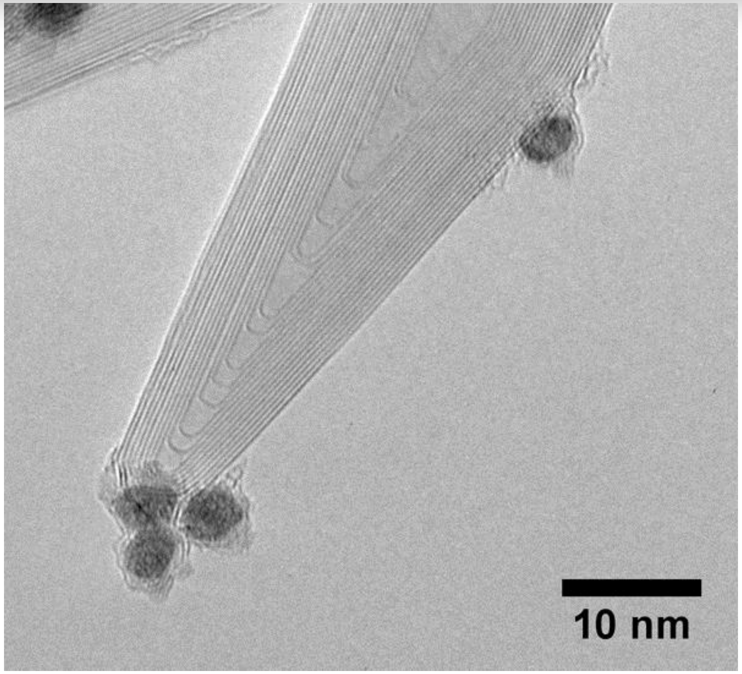
Tube apex and changes of curvature act as pinning sites

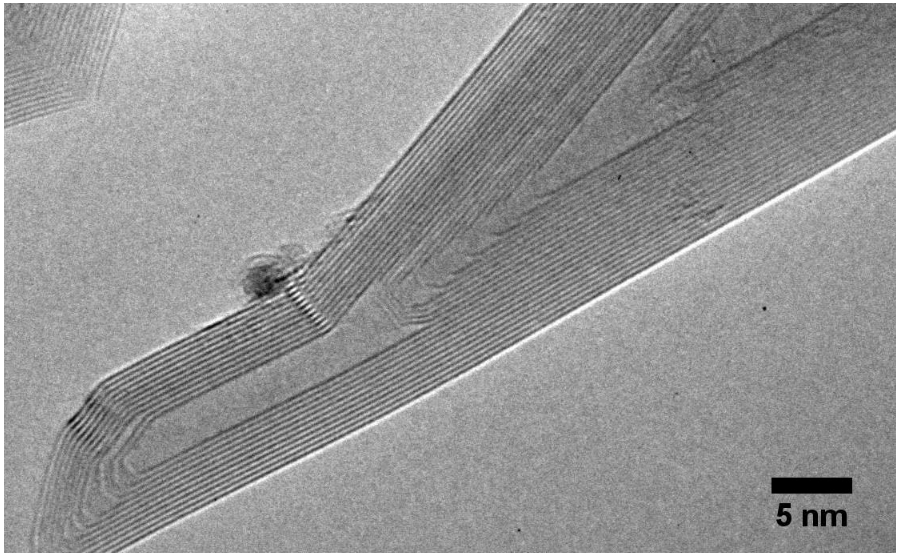


Defects

Enhanced particle/CNT interaction

Potentially interesting…

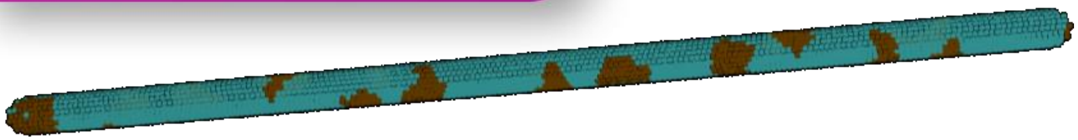




iLM INSTITUT LUMIÈRE MATIÈRE

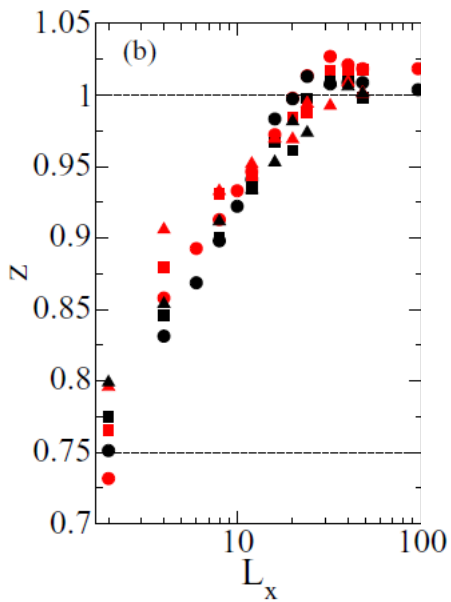
Theoretical investigation: 2D to 1D transition

R. Delagrange et al., Phys. Rev. B. **89**, 035425 (2014).



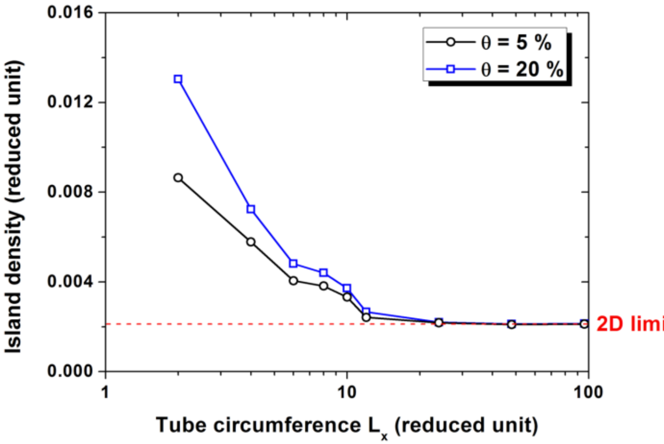
Kinetic monte-carlo simulations.

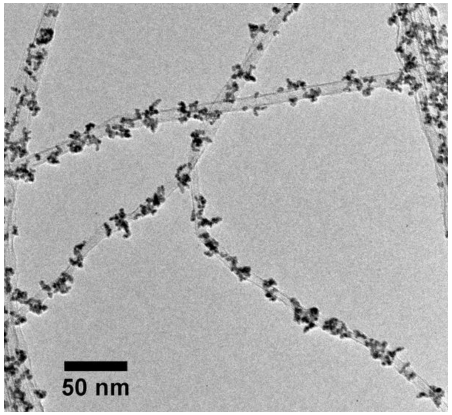
Transition from 2D to 1D behavior.



$$N \sim \theta^{1-z} R^{-\chi}$$

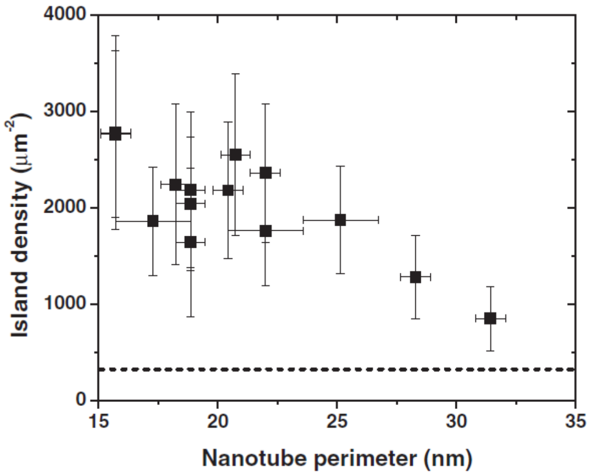
- N → Island density
- θ → Surface coverage
- R → Deposition rate





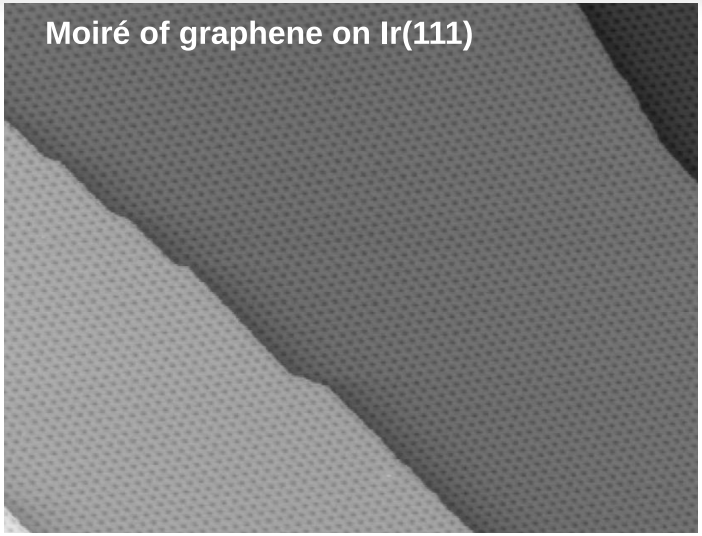
Higher island density for small diameter nanotubes.

Experimental observations consistent with the theoretical prediction.



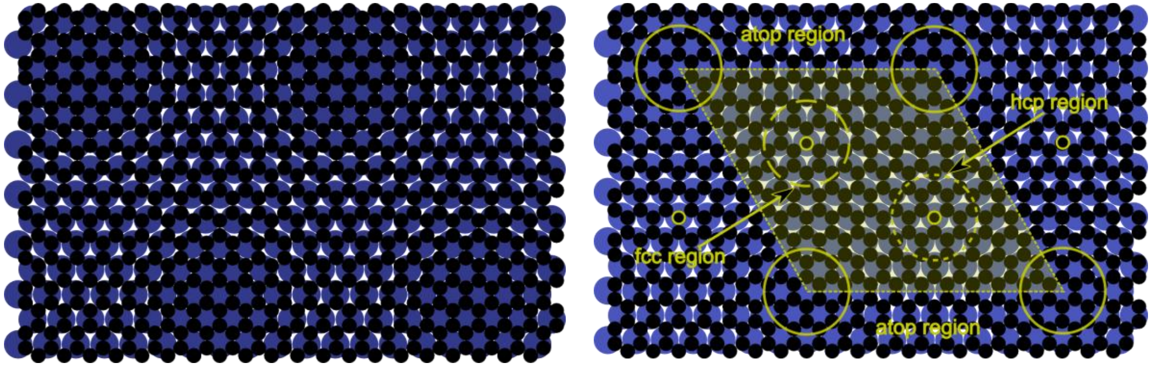
Cluster deposition on graphene / Ir(111)

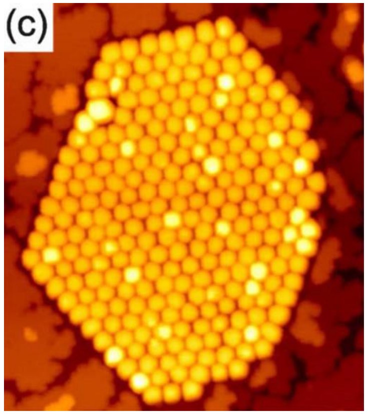
Idea: use the **moiré lattice** of graphene epitaxially grown on Ir(111) to obtain **arrays of particles**



J. Coraux *et al*., Nano Letters **8,** 565 (2008).

Lattice mismatch produces a moiré
→ specific sites with a 2.5 nm periodicity





✓ Organized growth of dots with atomic deposition

N'Diaye *et al*., New J. Phys. **11,** 103045 (2009); Phys. Rev. Lett. **97**, 215501 (2006).

✓ Self-organization using deposition of preformed clusters?

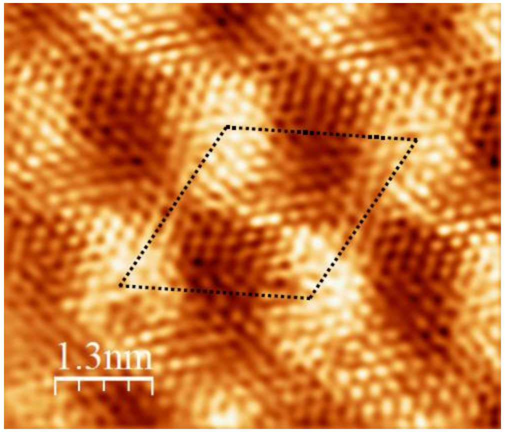
→ Deposition of Pt clusters (1.5 nm).

Collaboration with G. Renaud

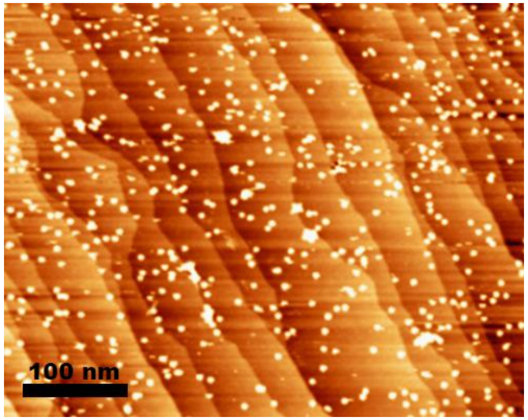
Agence Nationale de la Recherche ANR
NMGEM
NanoMagnetisme sur Graphène Epitaxié sur Métaux
ANR-2010-BLAN-1019-NMGEM

Pt clusters deposited on graphene / Ir(111)

Room temperature deposition of size-selected Pt clusters

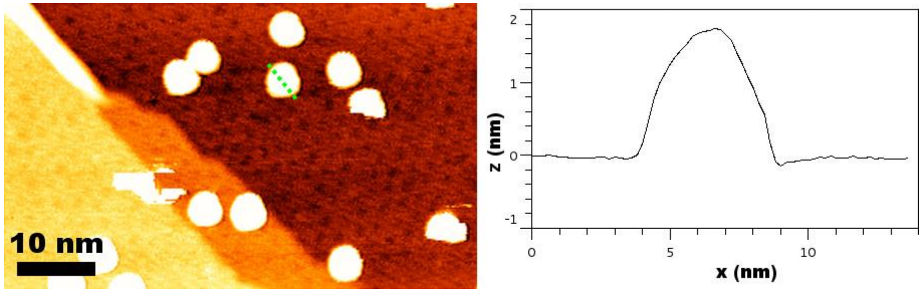


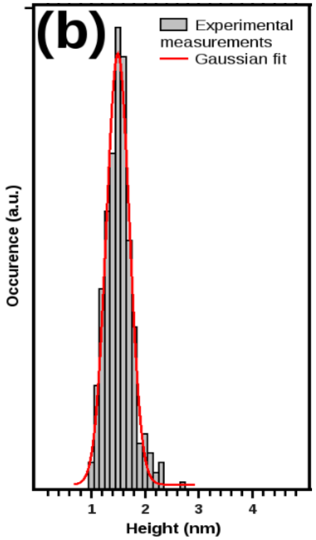
Moiré of the bare graphene/Ir(111) surface.



After Pt cluster deposition (low coverage).

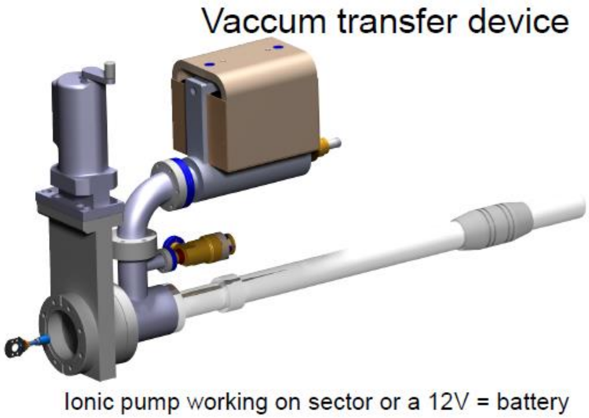
✓ In situ **STM observations.**

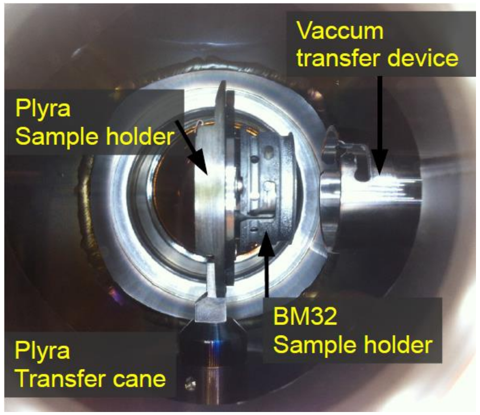




→ Low diffusion of the clusters.

✓ **X-ray experiments** at ESRF with UHV transfer from Lyon to Grenoble.

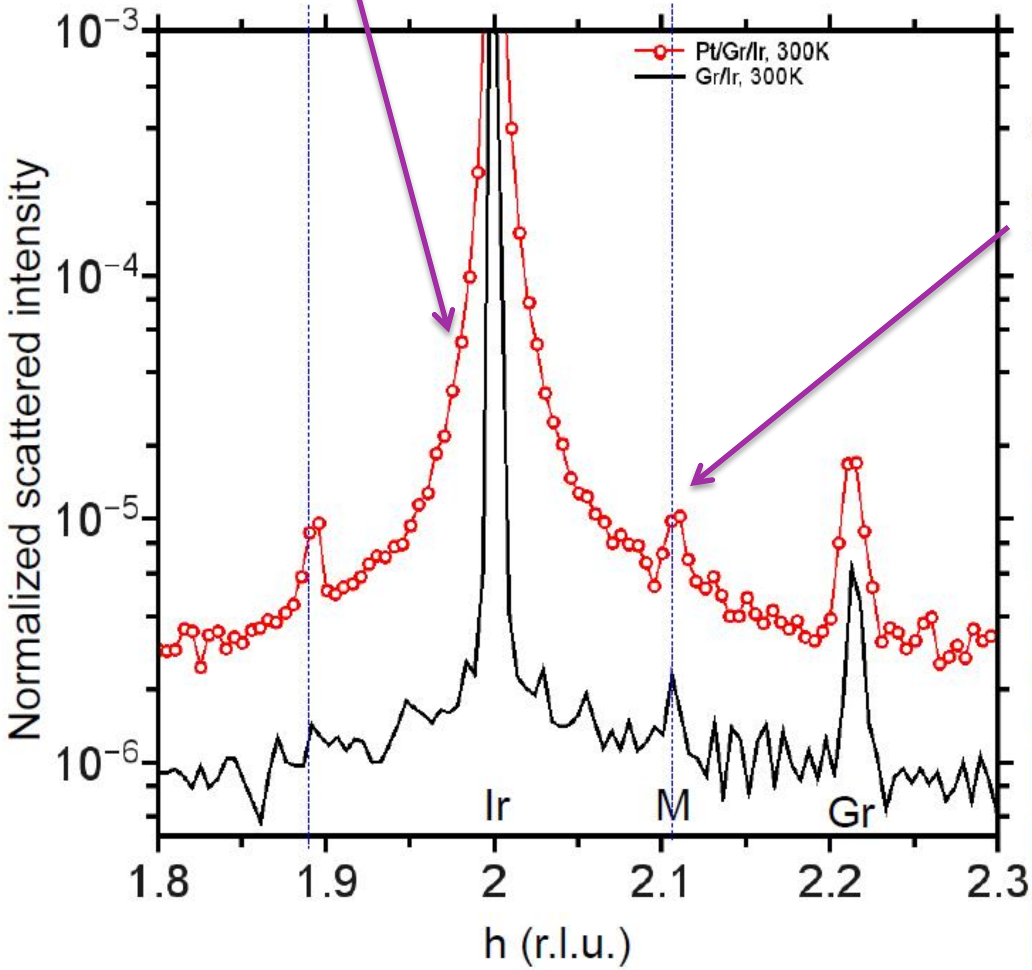




X-ray diffraction

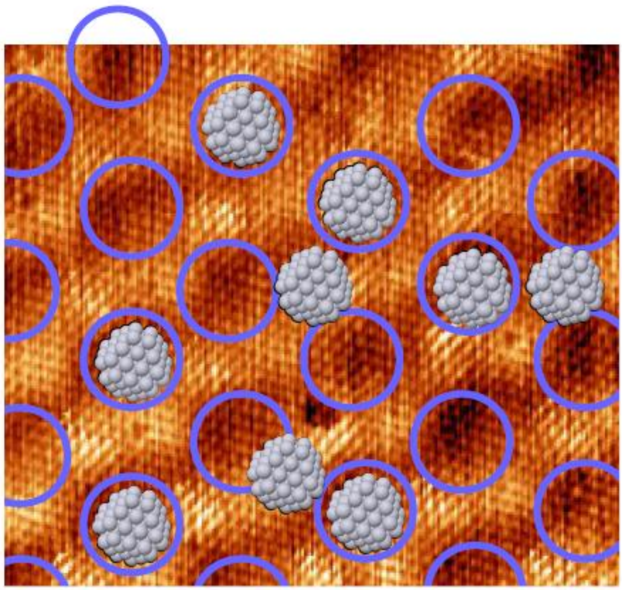
Grazing incidence XRD at ESRF (BM32 beamline).

Pt particles on epitaxy with the Ir substrate



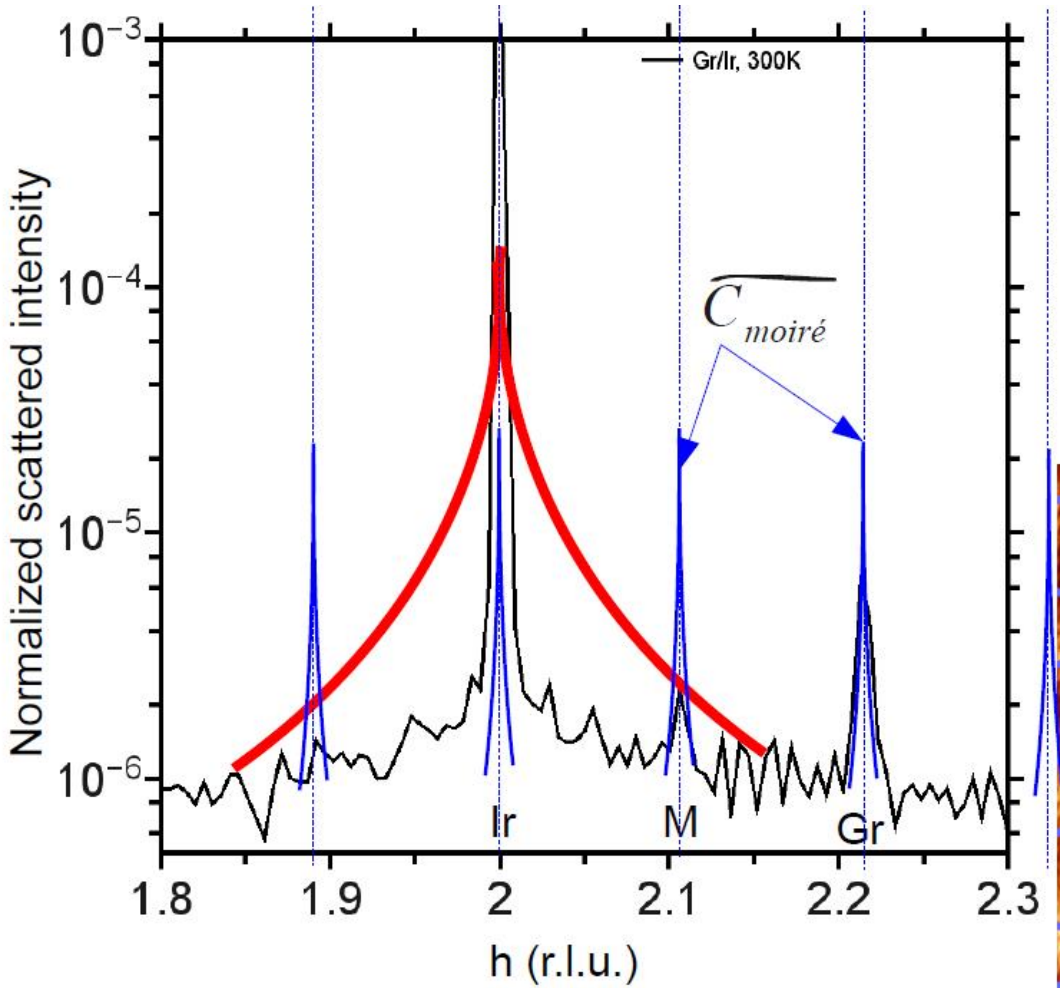
Some particles are randomly distributed

Some particles are pinned on a specific moiré site



Curves shifted for the eyes

X-ray diffraction



- Particles in **epitaxy, randomly** distributed

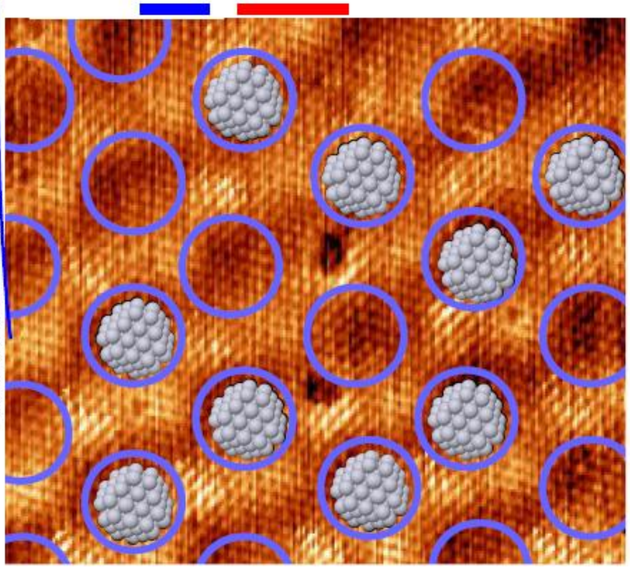
$N = F \times C_{Pt}$

$I = \tilde{F} \otimes \widetilde{C_{Pt}}$ ► **Broadening of the Ir peak**

- Particles in **epitaxy,** pinned on the moiré lattice

$N = C_{moiré} \otimes (F \times C_{Pt})$

$I = \widetilde{C_{moiré}} \times (\tilde{F} \otimes \widetilde{C_{Pt}})$

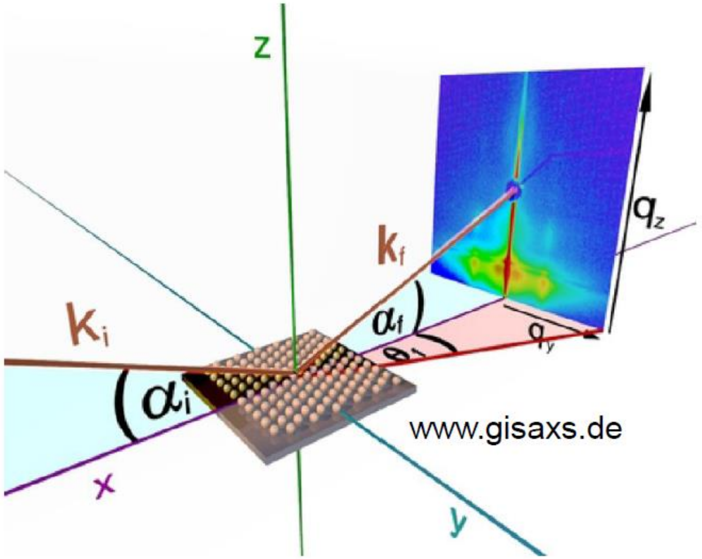


GISAXS

Grazing Incidence Small Angle Scattering (Decoupling approximation)

$$I(\boldsymbol{q}) = |\langle F(\boldsymbol{q})\rangle|^2 \times S(\boldsymbol{q}) + \underbrace{\langle |F(\boldsymbol{q})|^2\rangle - |\langle F(\boldsymbol{q})\rangle|^2}_{\text{Diffusive term}}$$

Information about the shape and distribution of nanostructures.



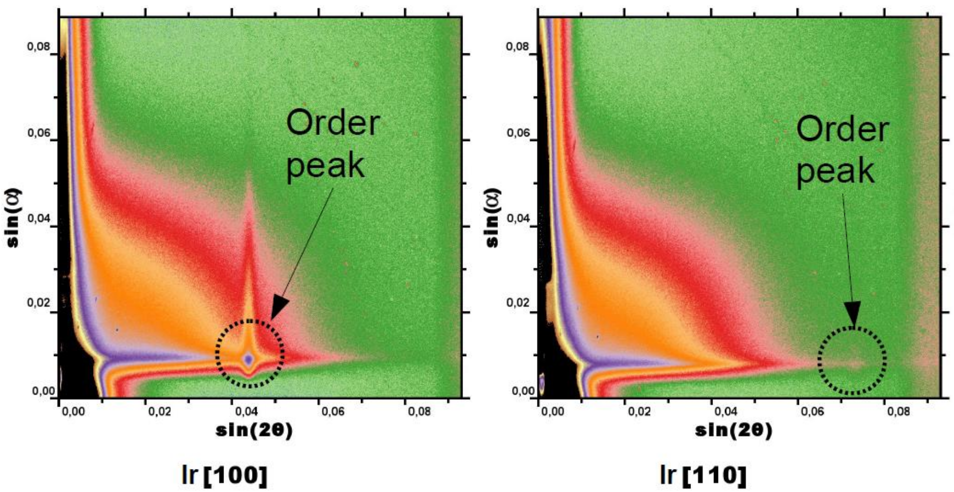
$I(\boldsymbol{q})$: *Scattered Intensity*

$F(\boldsymbol{q})$: *Form factor*

$S(\boldsymbol{q})$: *Interference function*

Hexagonal lattice of Pt clusters (lattice parameter = 2.5 nm)

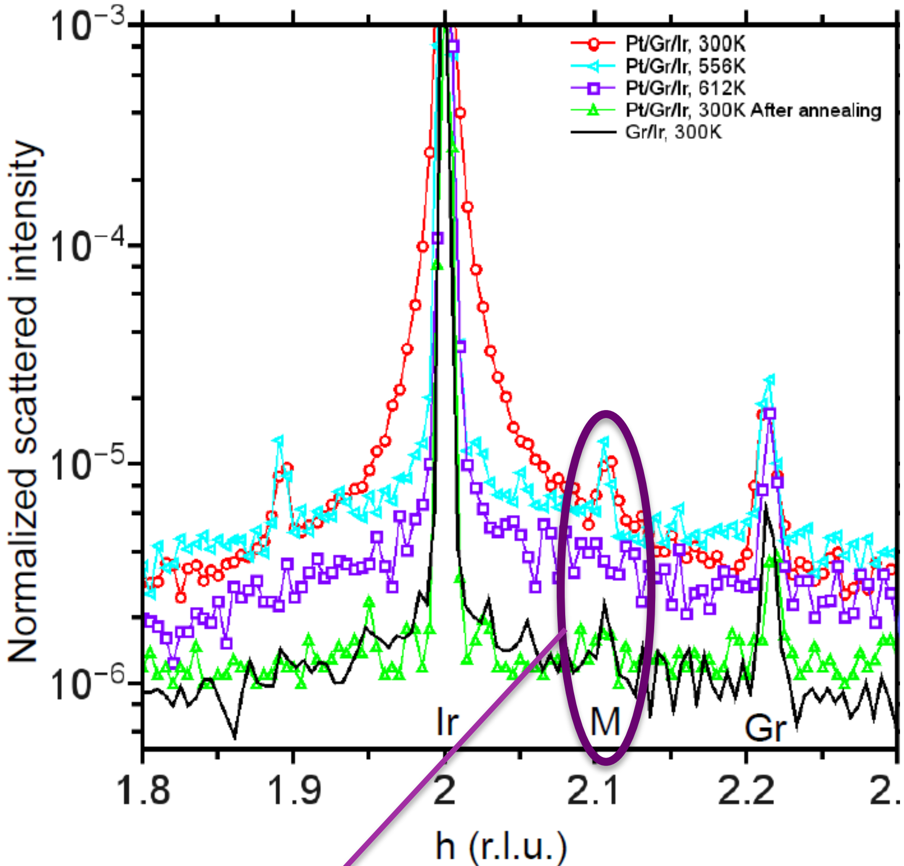
Pt clusters pinned on a specific moiré site!



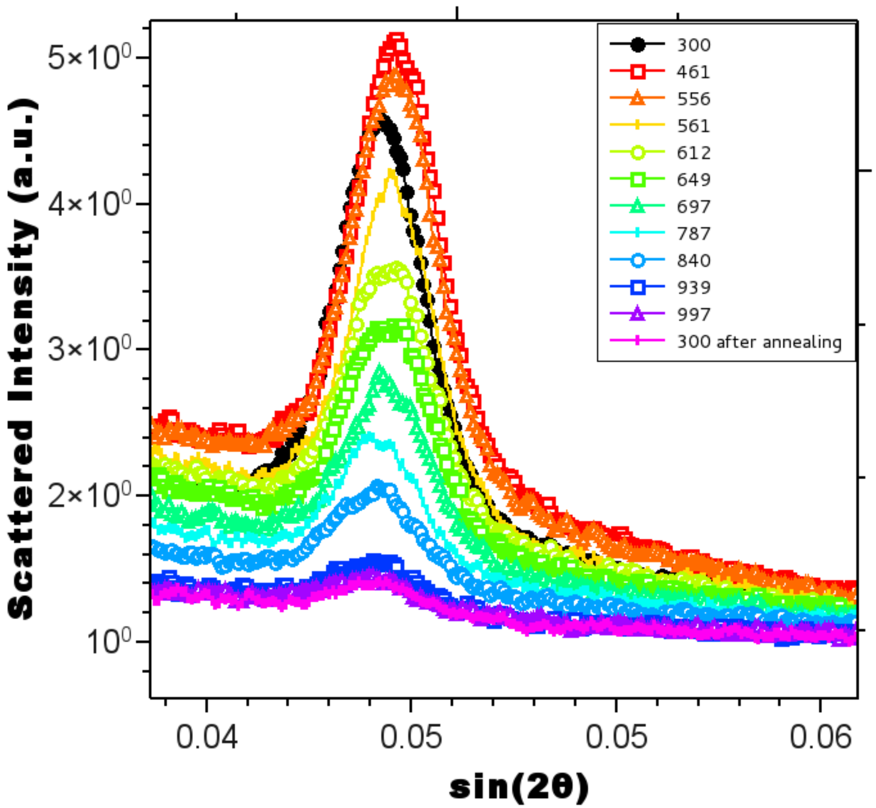
Evolution with temperature

Signature of the particle organization:

- Moiré peak in GIXRD (epitaxy is required)
- Order peak in GISAXS (no epitaxy needed)



No more moiré peak for T= 612 K



Pt particles are still organized for T = 612 K, without change of size.

Conclusion: Pt clusters on graphene

- ✓ Self-organization of preformed Pt clusters at room temperature, stable up to around 600 K.

- ✓ Epitaxy with the Ir surface

- ✓ Efficient pinning at moiré sites

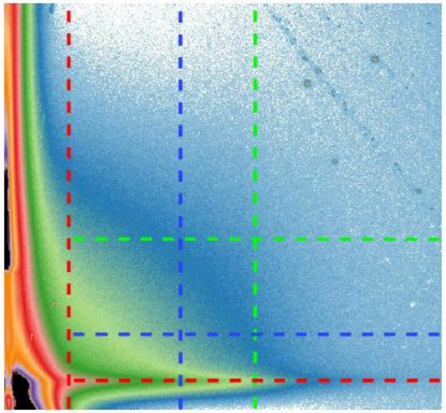
  ➡ Upon annealing, epitaxy is lost before the lattice order.

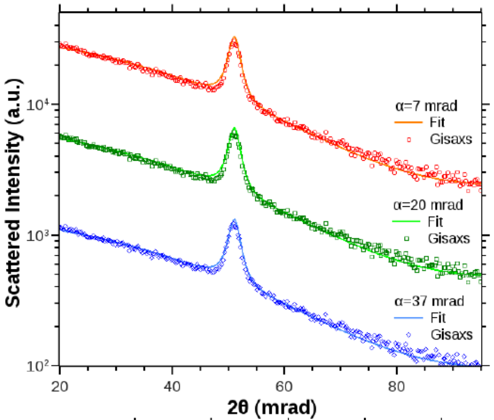
- ✓ Quantitative analysis of the proportion of clusters on the moiré lattice

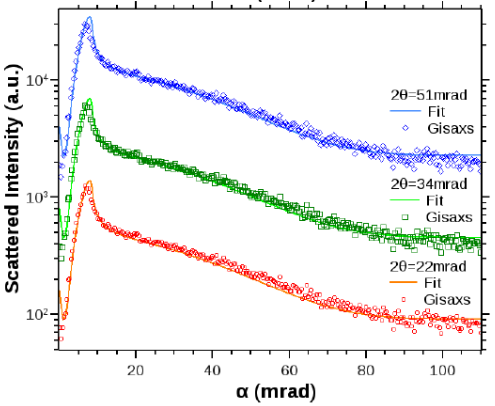
  ➡ GISAXS simulations needed (ongoing work).

- ✓ Deposition of FePt clusters on graphene

  ➡ Interesting for magnetism.







General perspectives

- Self-organization of nano-magnets (deposition on template surfaces).
- Understand size reduction effects in magnetic nanoalloys (exotic structures, magnetic transitions).
- Multifunctional systems (plasmonics, reactivity).
- Single particle measurements (XPEEM, transport, STM, microSQUID…)
- Superconducting clusters

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